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NATIONAL COMMUNICATIONS SYSTEM

ELECTROMAGNETIC PULSE (EMP) SURVIVABILITY OF TELECOMMUNICATIONS ASSETS

FEBRUARY 6, 1987

OFFICE OF THE MANAGER
NATIONAL COMMUNICATIONS SYSTEM
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This report focuses on the estimation of the effects of EMP on selected telecommunications assets. The list of critical assets identified in previous reports is refined to reflect the propose NETS network designs. The threat considered for the EMP effects evaluation if the 50 kV/m double exponential description of the early time portion of the high altitude EMP (HEMP) pulse ([redacted]) which represents the most significant EMP threat to telecommunications assets. Intermediate time EMP and magnetohydrodynamic EMP (MHD EMP) effects are not explicitly evaluated in this report. This report is also limited to typical installations of the selected assets; although versions of some equipment that have been explicitly hardened against EMP effects exist, these versions are not considered for this analysis.

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EXECUTIVE SUMMARY

BACKGROUND

In response to Executive Order (E.O.) 12472 and National Security Decision Directive 97 (NSDD-97), the Office of the Manager, National Communications System (OMNCS) has begun an electromagnetic pulse (EMP) mitigation program. The objective of this program is the removal of EMP as a significant impediment to timely re-establishment of regional and national telecommunications following an attack against the United States that includes high altitude nuclear detonations. The methodology for developing an EMP mitigation program plan was described in the NCS report "Electromagnetic Pulse Mitigation Program Approach" of July 1982. The program approach involves estimating the effects of EMP on telecommunications capabilities, assessing the impact of available EMP mitigation alternatives, and developing a comprehensive plan for implementing mitigation alternatives.

PROGRAM APPROACH

The approach to the NCS EMP mitigation program is illustrated in Exhibit ES-1. This approach is composed of the following activities:

- Identifying critical telecommunications assets
- Evaluating the effects of EMP on selected network elements
- Evaluating the effects of EMP on selected telecommunications networks
- Assessing alternative strategies for mitigating the effects of EMP.

The second activity is the subject of current efforts. The other three activities are addressed in current and future efforts.

The first activity is the identification of critical telecommunications assets based on postulated National Security and Emergency Preparedness (NSEP) telecommunications requirements. These requirements result from consideration of the evolving NSEP Telecommunications Architecture and National Security Telecommunications Policy (NSTP) initiatives such as the Nationwide Emergency Telecommunications System (NETS). Focusing on these requirements will emphasize the assets of greatest concern to NCS efforts, bound the effort required in this assessment, and preclude analysis of nonessential equipment.

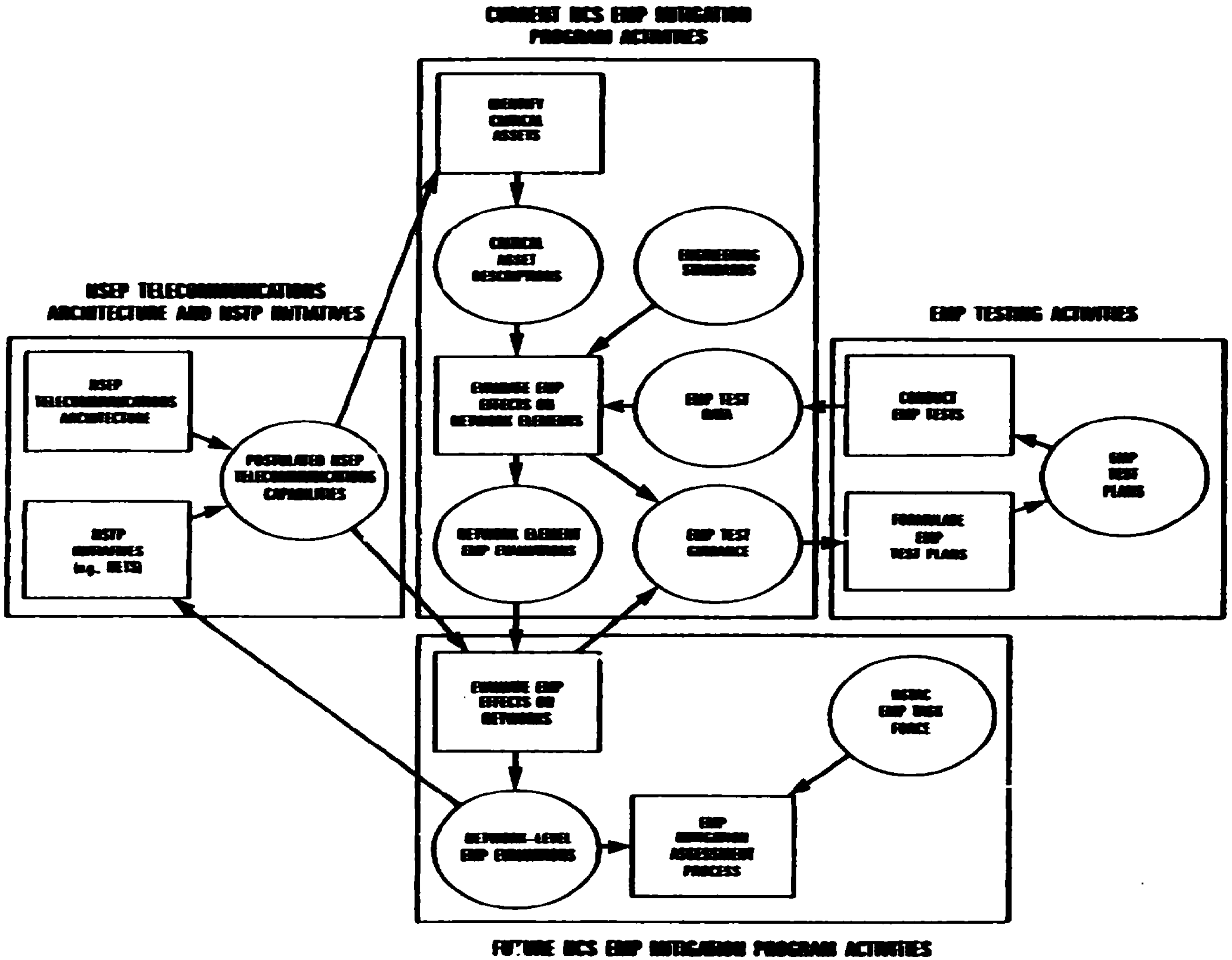

EXHIBIT ES-1. EMP Mitigation Program Approach

The second activity is the estimation of the EMP effects on selected network elements. In this activity, each selected asset is characterized from an EMP perspective. Applicable EMP test data and the standards and practices used by the telecommunications industry are analyzed. The results of this activity are estimates of the EMP responses of the selected network elements to EMP and recommendations for further analysis and testing to resolve remaining issues.

The third activity will evaluate the effects of EMP on telecommunications networks. Design approaches of interest to current NSTP initiatives and NSEP architectural analyses are reflected in the topologies of the networks evaluated; the results of the second activity are used to determine the EMP responses of the nodes and links of the networks evaluated. The results of this activity will be estimates of the responses of selected telecommunications networks to EMP, indications of the inherent survivability of network topologies of interest to NSEP telecommunications planners, and further guidance to EMP test planners.

The fourth activity will assess alternative EMP mitigation strategies. Various alternatives for mitigating the effects of EMP on national telecommunications capabilities can be identified for consideration in the assessment process. Based on the results of the network-level EMP evaluations and inputs from the National Security Telecommunications Advisory Committee, the costs, benefits, and risks of implementation of each of the identified mitigation alternatives will be determined. This activity will result in a recommended composite strategy for the mitigation of the effects of EMP on regional and national telecommunications capabilities.

SCOPE OF REPORT

This report focuses on the estimation of the effects of EMP on selected telecommunications assets. The list of critical assets identified in previous reports is refined to reflect the proposed NETS network designs. The threat considered for the EMP effects evaluation is the 50 kV/m double exponential description of the early time portion of the high altitude EMP (HEMP)* pulse (Ref. 1) which represents the most significant EMP threat to telecommunications assets. Intermediate time EMP and magnetohydrodynamic EMP (MHD EMP) effects are not explicitly evaluated in this report. This report is also limited to typical installations of the selected assets; although versions of some equipment that have been explicitly hardened against EMP effects exist, these versions are not considered for this analysis.

CRITICAL ASSET IDENTIFICATION

The list of critical assets identified in previous reports for this program are refined in this report to reflect the proposed NETS network

* Throughout the report, the terms HEMP and EMP are both used to refer to this double exponential pulse.

designs. Assets are chosen from that list of assets for inclusion in this report based on currently available test data and theoretical analyses; the remaining assets will be evaluated as data become available. The switching systems evaluated in this report are the 4ESS™ and 5ESS™ systems. The transmission facilities evaluated in this report are the T1 and FT3C carrier systems, the L4 and L5 coaxial cable systems, and the TD-2 microwave system. Network signaling and synchronization are also evaluated based on their system designs and their dependence on the other assets evaluated.

EVALUATION OF EMP EFFECTS

The evaluation of the effects of EMP on the selected assets requires the electromagnetic coupling characterization of each asset and then the identification of significant parameters affecting EMP responses of telecommunications assets along with determination of typical stress levels. The HEMP threat is described, including its origin and the characteristics of the electromagnetic field. Various EMP effects are characterized, including direct illumination effects, coupling to aerial and buried cables, and coupling to vertical structures. The mitigating effects of typical construction and installation practices on EMP-induced stress levels is evaluated, including the effectiveness of the shielding provided by building walls and cable sheaths, of grounding and bonding practices, and the use of surgelimiting and filtering devices. Both good and bad practices are discussed for use in the subsequent analyses of the selected assets.

The evaluation of the effects of EMP on the selected assets uses available test data, theoretical analyses, stress level calculations, and the standards and practices of the telecommunication industry. Test reports and analyses are analyzed to verify approach, results and conclusions. The EMP threat description used is compared to the 50 kV/m double exponential pulse description and measured or predicted stress levels are compared to those predicted in this report. The equipment configurations are compared to typical installations of the selected assets. Based on these comparisons, the results of the tests and theoretical analyses are used to draw conclusions about typical configurations of the assets.

The standards and practices used by the telecommunications industry are used where available test data and theoretical analyses are insufficient to draw conclusions. The standards and practices define typical installation procedures, operational limits, required electromagnetic protection, and typical noise and transient levels. These standards and practices do not typically deal with EMP; however, lightning induced transients and electromagnetic interference are frequently addressed. Each applicable standard or practice is analyzed to determine the effect its implementation has on the EMP response of the selected network elements. The results of the evaluation of standards and practices are combined with available test data and theoretical analyses to arrive at the conclusions presented in this report.

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CONCLUSIONS

The conclusions concerning the effects of EMP on selected network elements follow:

- The unhardened T1 carrier system is vulnerable to the effects of HEMP. T1 system elements have been exposed to simulated low-level HEMP fields; the results were then analytically extrapolated to full threat values. Lightning protected repeaters were not damaged; test results for repeaters without lightning protection are inconclusive. D4 channel banks suffered significant damage during testing at transient stress levels that could occur in the central office environment; however, further tests and analyses are required to determine the applicability of these results to typical D4 installations. A hardened T1 carrier system, including EMP-protected D4 channel banks and repeaters, was tested at field strengths up to 80 kV/m and proved robust to the effects of HEMP.

- The FT3C multi-mode system is vulnerable to the effects of HEMP. Threat-level fields and injected currents did not produce any signal disruptions or service-affecting hardware damage during testing of the optical cable and splice case; both elements appear to be survivable to the effects of HEMP. Available test data on the survivability of CO and LRS equipment are inconclusive, since threat-level currents were not injected into all subsystems. Unmodified power converters were shown to be vulnerable to threat-level transients. Power converters incorporating several hardware modifications proved robust, although the test configurations using modified power converters were not typical of most LRSs and COs. The modified power converters, therefore, can not be considered survivable to EMP based on available test data. Because both line repeater station (LRS) and central office (CO) equipment rely upon the power converters to power them, the entire FT3C system must be considered vulnerable.

- The L4 and L5 systems are robust to HEMP effects. These systems are designed for survival in a nuclear environment; all cable is buried and repeaters are well bonded and well grounded. Detailed computer analyses and HEMP simulation tests indicate that although some temporary system outages will occur, no equipment will be damaged as a result of HEMP.

- The TD-2 microwave radio system is survivable to HEMP effects. Threat level, free-field HEMP simulation testing has produced upsets such as the activation of protection switching and frequency shifting, but has produced no failures. Low-level current-injection tests caused no failures; high-level testing has not been done. However, comparison of predicted HEMP-induced currents to expected lightning-induced transients on microwave towers indicates that TD-2 systems are also survivable against conducted transients.

- The 5ESS switching system is vulnerable to the effects of HEMP. Several service-affecting hardware failures occured under exposure to threat-level fields. With several hardware modifications in place, the hardened 5ESS switch suffered no permanent hardware damage, although a significant number of calls were dropped and call processing capability was reduced. Manual recovery was required to restore call processing efficiency to greater than 99%; however, most central offices housing 5ESS switches are not staffed and the survivability of remote links has not been demonstrated. To ensure the survivability of a particular 5ESS system requires verification that the identified hardware modifications have been installed and verification that either the site will be staffed or that a survivable remote link has been established.

- Existing test data on the 4ESS switching system are insufficient to assess its vulnerability to HEMP. No tests or theoretical analysis of the HEMP response of the 4ESS system exist; the results of the 5ESS system assessment cannot be applied to the 4ESS system. In the absence of test data, no definite conclusions can be drawn.

RECOMMENDATIONS

The recommendations concerning future efforts in this program follow:

- The effects of HEMP on the 4ESS switching systems should be determined through test and analysis. The configuration assessed should include typical line termination equipment and appropriately placed lightning protection devices. Typical lengths of the Peripheral Unit Bus (PUB) should also be included.

- The results of the current study to determine the sensitivity of the network-level HEMP-effects model should be used to identify and prioritize critical telecommunications assets. The NCS has developed a model to predict the effects of HEMP-induced equipment failures on telecommunications networks. Current efforts include a study to determine the sensitivity of predicted network performance to input data. The telecommunications equipment critical to the NSEP capabilities of the NCS should be identified and prioritized based on the results of the sensitivity study. This prioritization should be used as a basis for allocating resources for future tests and analysis of telecommunications equipment in support of this program.

- Remaining issues concerning 5ESS switching systems should be resolved by testing and analysis. The survivability of remote links to 5ESS sites should be determined. Further testing of existing 5ESS power system rectifiers is needed to verify their survivability. Several new models of rectifiers are planned for use in future 5ESS power systems; these rectifiers must be thoroughly tested before any system in which these are used can be considered survivable to EMP.

- Remaining issues concerning FT3C carrier systems should be resolved by testing and analysis. Threat-level currents should be injected into all CO and LRS equipment subsystems, so that their survivability can be determined. Further testing of EMP-hardened power converters using test configurations typical of most LRSs and COs is needed to verify their survivability to EMP. Single-mode fiber optic systems should be tested to assess their survivability to EMP, and a comparison should be made to the results of the FT3C multi-mode system assessment.

- The HEMP response of TD-3 microwave systems should be evaluated through test and analysis. The TD-2 microwave system is based on vacuum tube technology; the TD-3 system is a solid state replacement for the TD-2 system. Solid state components tend to be less survivable than their vacuum tube equivalents. This evaluation is required to determine if the TD-3 system is as robust as the TD-2 system.

- Remaining issues concerning T1 carrier systems should be resolved by testing and analysis. Typical T1 line repeaters that do not have lightning protection need to be tested since not all repeaters in the PSN will have lightning protection. In addition, typical splice case configurations need to be tested with current injection on the sheath, as coupling to signal wires from bond straps can be a significant part of the threat to T1 line and office equipment.

- The EMP responses of similar equipment from different vendors should be analyzed to evaluate methods of relating test results for one system to the survivability of another. Various vendors manufacture similar equipment for the telecommunications industry, e.g., T1 line termination equipment, channel banks, and local, digital switching systems. The ability to relate the survivability of similar pieces of equipment would minimize the amount of testing required to assess the effects of HEMP on telecommunications networks.

- The present analysis should be extended to include the new Department of Defense approved HEMP threat (Ref. 2). The analysis should include the early time, mid-time, and late time (MHD EMP) effects. The faster rise time of the new threat can create higher peak level transients on cables and antenna leads. The MHD EMP can create large transients on very long cables. These effects may create additional EMP vulnerabilities in telecommunications assets.

1.0 INTRODUCTION

1.0 INTRODUCTION

In response to Executive Order (E.O.) 12472 and National Security Decision Directive 97 (NSDD-97), the Office of the Manager, National Communications System (OMNCS) has begun an electromagnetic pulse (EMP) mitigation program. The objective of this program is the removal of EMP as a significant impediment to timely re-establishment of regional and national telecommunications following an attack against the United States that includes high altitude nuclear detonations. The methodology for developing an EMP mitigation program plan was described in the NCS report "Electromagetic Pulse Mitigation Program Approach" of July 1982. In that document, essential program steps were defined as: identification of Public Switched Network (PSN) assets critical for reconstitution, estimation of the effects of EMP on these assets and the networks in which they are embedded, assessment of the impact of available EMP mitigation alternatives, and development of a comprehensive plan for implementing mitigation alternatives.

1.1 PURPOSE

The purpose of this report is to present the results of analyses of the effects of EMP on selected elements within the nation's telecommunications networks. These results are required for the next step in the EMP mitigation program, in which the network-level effects of EMP on selected telecommunications networks are to be evaluated. This report also provides guidance for future EMP testing and analysis of telecommunications network elements.

1.2 SCOPE

This report focuses on the estimation of the effects of EMP on selected telecommunications assets. The list of critical assets identified in previous reports is refined to reflect evolving NSEP telecommunications capabilities, especially proposed NETS network designs. The threat considered for the EMP effects evaluation is the 50 kV/m double exponential description of the early time portion of the high altitude EMP (HEMP)* pulse (Ref. 1). Because intermediate time EMP and magnetohydrodynamic EMP (MHDEMP) affect fewer types of telecommunications equipment, equipment responses to these EMP components are not evaluated. The discussions in this report are also limited to typical installations of the selected assets; although versions of some equipment that have been explicitly hardened against EMP effects exist, these versions are not considered for this analysis.

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* Throughout this report, the terms EMP and HEMP are both used to refer to this double exponential pulse description of the early time portion of the HEMP threat.

1.3 ORGANIZATION

Chapter 2.0 describes the context of the current analysis and provides details on the approach for evaluating network elements. The unique feature of the approach is that design and construction standards and practices are used in conjunction with EMP test data to draw conclusions about specific types of telecommunications equipment. This obviates the requirement for a costly, site-by-site EMP assessment.

Chapter 3.0 identifies telecommunications assets critical to continued connectivity within the PSN and lists the specific equipment types evaluated in this analysis. Equipment is identified in four categories: switching, transmission, synchronization, and signaling.

Chapter 4.0 characterizes the electrical transients induced by HEMP on telecommunications assets. The estimated transient levels are based on EMP simulator test data supplemented by analysis. Significant physical parameters affecting these transients and the standards and practices used to mitigate conventional transients (i.e., lightning, RFI, power faults) are also discussed. Good EMP protection practices are presented for comparison with conventional protection techniques and for reference in the assessments presented in Chapters 5.0 and 6.0.

In Chapter 5.0, transmission facilities are evaluated to estimate HEMP responses; switching systems are evaluated in Chapter 6.0. In each chapter, the important HEMP coupling modes and paths are defined and HEMP induced stress levels are estimated; these stress levels are compared to equipment susceptibility levels to assess HEMP effects. These assessments incorporate results of HEMP simulation test programs, results of previous theoretical analyses, and standards and practices used by the telecommunications industry.

Conclusions and recommendations are presented in Chapter 7.0.

2.0 EMP EVALUATION DESCRIPTION

2.0 EMP EVALUATION DESCRIPTION

The estimated effects of EMP on the selected network assets presented in this report are part of a more comprehensive analysis of EMP effects of concern to NSEP telecommunications planners. This overall analysis is actually composed of four distinct but interrelated activities:

- Identification of critical telecommunications assets
- Evaluation of the effects of EMP on selected network elements
- Evaluation of the effects of EMP on networks of interest to NSEP telecommunications planners
- Assessment of alternative strategies for mitigating the effects of EMP.

Each activity is described in this chapter. Particular attention is given to the methodology used in the current evaluation of selected network elements. Exhibit 2-1 illustrates the overall approach to evaluating the effects of EMP on telecommunications systems and their network elements.

2.1 IDENTIFICATION OF CRITICAL ASSETS

The first step in the overall assessment of the effects of EMP is to identify generic types of equipment, i.e., critical assets, based on postulated NSEP telecommunications capabilities within the PSN. These capabilities result from consideration of the evolving NSEP Telecommunications Architecture, and National Security Telecommunications Policy (NSTP) initiatives such as the Nationwide Emergency Telecommunications System (NETS). Detailed assessment of the effects of EMP is limited to those assets considered critical to the reconstitution of nationwide telecommunications connectivity. Focusing on these critical assets emphasizes the assets of major concern to NCS efforts, sets limits on the required effort, and precludes the analysis of nonessential equipment.

Critical telecommunications assets were identified in a previous study (Ref. 3). That list has been updated to reflect new information on the functions and structure of the PSN, and the requirements for current NCS technical initiatives. The critical assets used for this assessment are presented in Chapter 3.0.

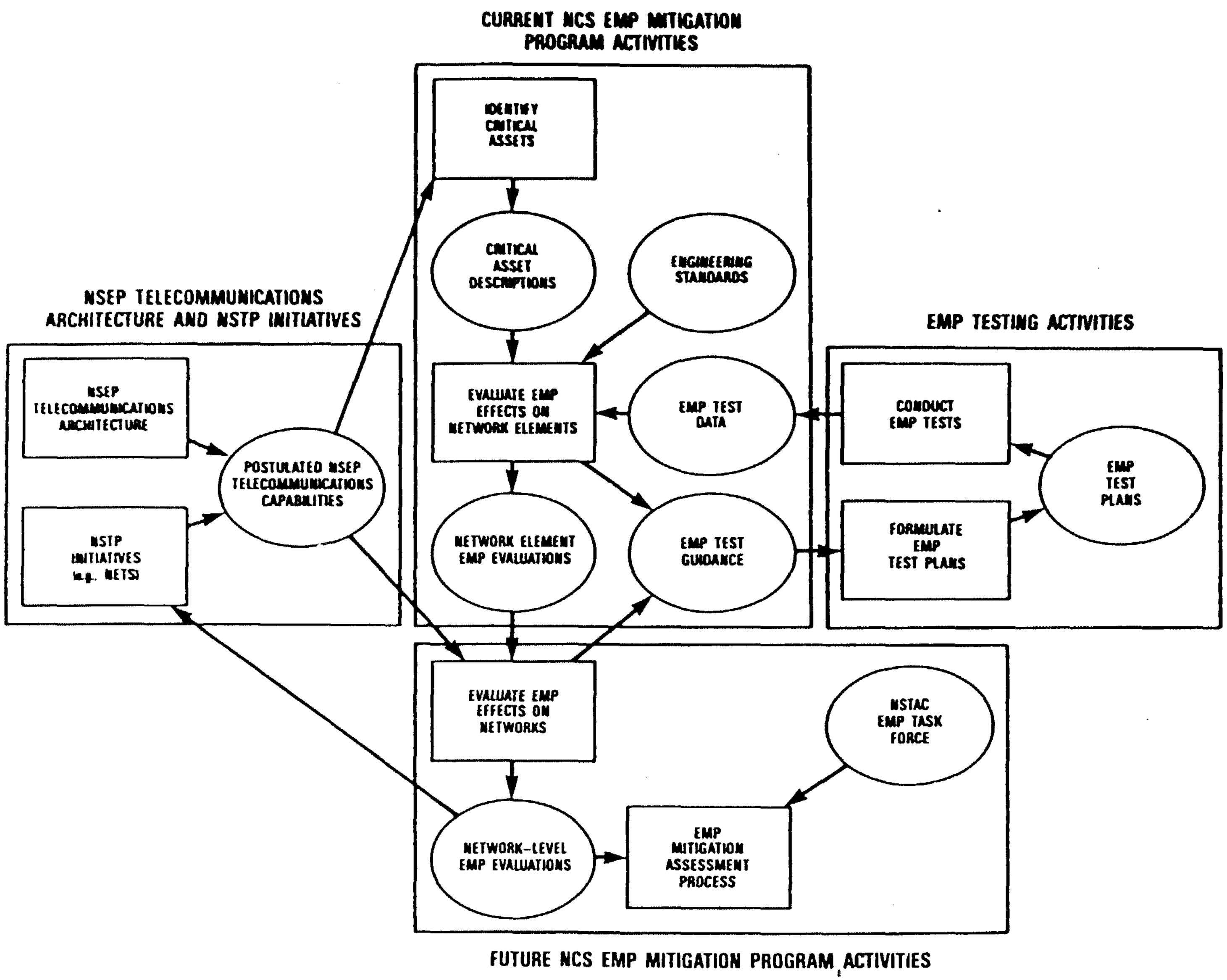

EXHIBIT 2-1. EMP Mitigation Program Approach.

2.2 EVALUATION OF THE EFFECTS OF EMP ON NETWORK ELEMENTS

The second step in the overall evaluation, and the main subject of this report, is an evaluation of the effects of EMP on selected telecommunications assets used by the nation's local and interexchange carriers. Proceeding from the identification of critical assets, the evaluation approach used in this analysis consists of the following basic elements:

- Characterization of assets from an EMP perspective
- Identification of engineering standards and practices
- Evaluation of EMP effects on selected assets.

The approach is shown in Exhibit 2-2.

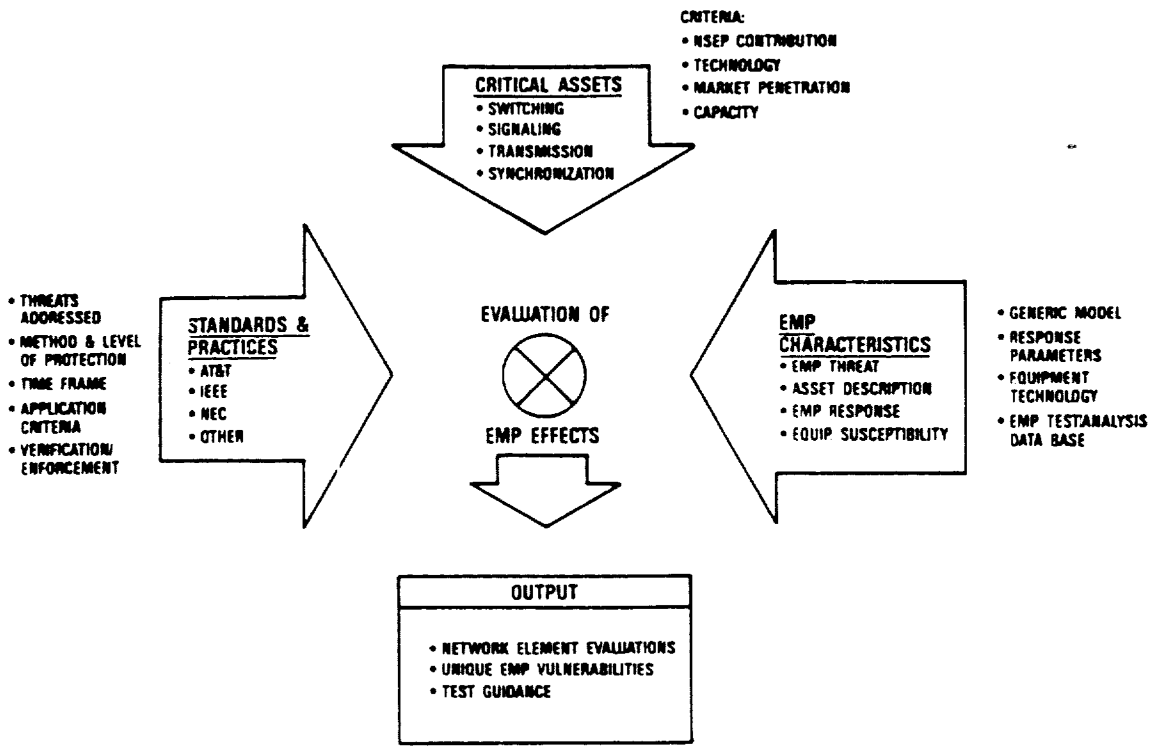

EXHIBIT 2-2. Approach To The Assessment Of EMP Effects On Network Elements.

The result of this analysis is an estimate of the HEMP-induced effects on specific types of equipment (e.g., 4ESS or 5ESS switches, microwave transmission systems) for use in system-level analyses of telecommunications network responses to EMP. Information shortfalls are identified along with recommendations for further analysis and testing to resolve remaining issues. Information shortfalls include those cases where testing has not been conducted and where standards and practices are inadequate for relating untested equipment to available test results with confidence.

The evaluations of network elements will be used as guidance for planning Government-sponsored EMP testing. These evaluations will also be used in analyses of the network-level effects of EMP on selected telecommunications networks.

2.2.1 EMP Characterization of Selected Assets

The determination of the EMP characteristics of selected assets begins with the definition of EMP stress levels. The determination is based on the following factors:

- EMP threat characterization
- Coupling characterization
- Engineering standards and practices.

A brief description of the EMP threat provides the basis for describing coupling characteristics. The coupling characteristics treated here are cable coupling and direct illumination effects. For each type of telecommunications asset studied, a generic model is developed based on the physical characteristics of typical configurations. All of the characteristics that are important to the analysis of the effects of EMP on the particular asset are included.

The model uses the zone and boundary model of typical EMP analyses (see Exhibit 2-3). As used here, boundary is identified as an electromagnetic barrier, which is usually a physical surface such as a wall, an equipment rack, a cabinet, or a cable sheath. Some boundaries provide little or no electrical protection, whereas others may be highly effective metallic shields. Zones are the volumes defined by the boundaries. Analysis of the EMP stress is performed at each boundary. The stress at boundary 1 includes the incident electric field and the transients that are coupled into external conductors. The stress at boundary 2 includes the electric field in zone 1, the portion of the conducted transients that have penetrated boundary 1, and the transients that are coupled into the conductors within zone 1.

2.2.2 Identification of Applicable Data

The next step is to identify EMP test data and the standards and practices that apply to the design and construction of the selected telecommunications assets under study. Of critical interest are the methods used to conduct tests, the EMP simulator field levels, the configuration of the equipment being tested, and the relationship between the equipment tested and typical equipment as defined by standards and practices. For this report, the primary sources of data on typical equipment are published standards and internal AT&T standards and practices.

2.2.3 Evaluation of the Effects of EMP on Selected Assets

The final step is to estimate the EMP responses for each of the chosen network elements. For each of the identified assets, all available data are analyzed along with the estimated stress levels. This analysis is used to estimate the effects of EMP on the particular asset and to identify unique vulnerabilities.

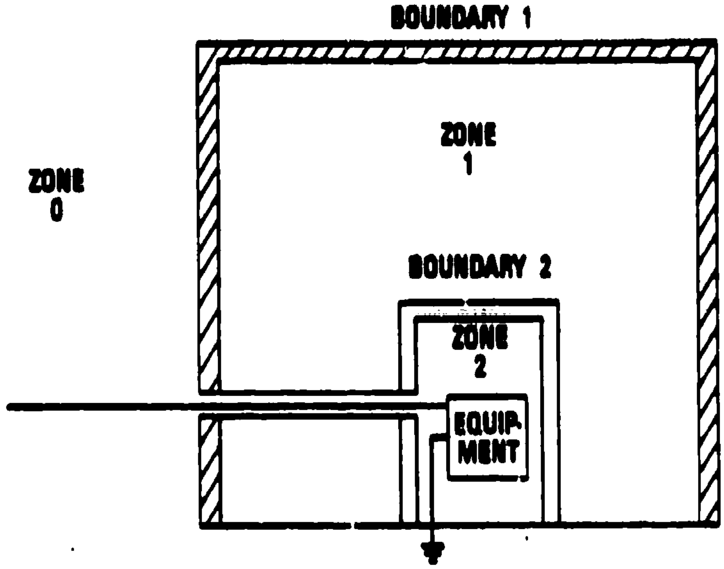

EXHIBIT 2-3. Zone-Boundary Model.

2.3 EVALUATION OF NETWORK-LEVEL EMP EFFECTS

One of the objectives of evaluating the effects of EMP on particular network elements is to provide data for evaluations of the network-level effects of EMP. The proposed approach to network-level evaluations is introduced in this report to indicate a particular use for the results of analyses of network elements. The results of network-level studies will be the subject of future reports.

Exhibit 2-4 illustrates the approach to be followed during network-level evaluations. The major inputs come from the results of evaluations of particular network elements, and from NSTP initiatives and NSEP architectural analyses. The results of the evaluation of network elements will provide the data for estimating failure probability distributions of network components as a function of tested EMP stress levels. NCS technical initiatives will be used to determine the nature of the telecommunications networks to be evaluated for the network-level effects of EMP. At first, network-level evaluations will focus on NETS, using the most current description of a NETS system topology available from AT&T. A network connectivity analysis model will be used to estimate EMP effects on network physical connectivity.

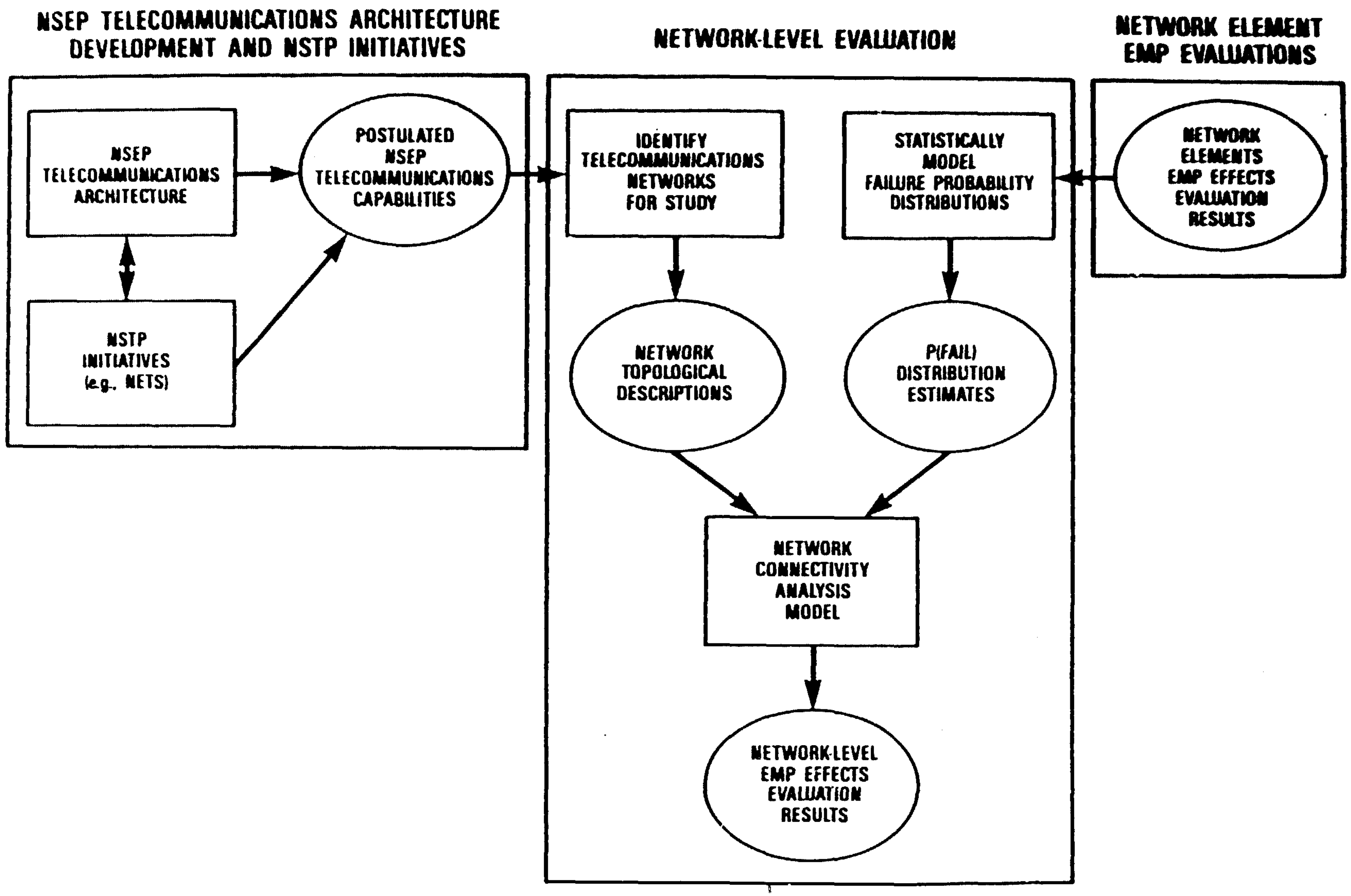

EXHIBIT 2-4. Approach To The Assessment Of EMP Effects On Networks.

2.4 ASSESSMENT OF EMP MITIGATION ALTERNATIVES

The ability to evaluate the network-level effects of EMP will allow planners to assess the efficacy of alternative strategies for mitigating the effects of EMP. Network element EMP mitigation strategies, which would affect the estimated failure probability distributions, will be evaluated based on their expected contribution to the maintenance of physical connectivity. Likewise, system topological design approaches will be evaluated based on overall expected connectivity performance in the face of EMP stress. Finally, network-level analyses will be used to provide further guidance to EMP test planners by identifying additional network elements critical to the maintenance of connectivity.

3.0 CRITICAL ASSET IDENTIFICATION

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The first step in the EMP evaluation approach described in Chapter 2.0 is to identify critical assets within the PSN. This chapter describes the rationale behind the critical assets identification process, and indicates those particular equipment types that are being considered in the current EMP effects evaluation.

3.1 ASSET IDENTIFICATION RATIONALE

The purpose of identifying critical assets of the PSN is to focus EMP analyses on those telecommunications assets that can contribute most toward the development of a capability to reconstitute communications in an emergency. This ensures that the EMP evaluations remain focused on those telecommunications assets that can provide the greatest contribution to critical network operations and reconstitutability. Such NCS initiatives as Commercial Satellite Survivability (CSS), NETS, Carrier Interconnect, and the NSEP Telecommunications Architecture contribute to network connectivity in a stressed environment and enhance the reconstitution of critical communications. The value of these initiatives is directly proportional to the survivability of particular classes of network facilities including:

- Switching
- Transmission
- Signaling
- Synchronization.

The objective of the critical asset identification process is to determine which specific types of equipment within these individual classes are particularly important to the overall NCS objective of achieving survivable and reconstitutable telecommunications capabilities. This importance may be due to the prevalence, capacity, or functional criticality of particular equipment types. Earlier approaches used in the identification process are described in NCS EMP Mitigation Program: Identification of Critical Telecommunications Facilities and an Approach for their EMP Evaluation, National Communications System, June 1983. That reference also presents the results of the initial critical asset identification using the described methodology. A more refined set of critical assets is given in NCS EMP Mitigation Program: Evaluation of Facility EMP Vulnerabilities - Interim Report, National Communications System, February 1984.

In this report, the results of the previous critical asset analyses are further refined to include considerations of the NCS initiatives which rely on certain PSN equipment types. The NETS project is the primary influence on critical asset identification. In the remainder of this section, the switching, transmission, signaling, and synchronization needs of NETS are emphasized, and the equipment types that are useful to NETS objectives are identified. In addition, the subset of these assets that are evaluated in subsequent sections of this report are noted. This subset represents those assets for which test data and analysis results are currently available. The remaining critical assets will be evaluated as test data become available.

3.2 SWITCHING

Based on proposed NETS configurations within the AT&T network, the two switches of primary importance to NETS are the Western Electric 4ESS switch and 5ESS switch. Switches in other networks that provide significant opportunities for supporting NETS include:

- Western Electric 1AESS and 1ESS switches
- Northern Telecom DMS 250, DMS 200, DMS 100/200, and DMS 100 switches
- Automatic Electric 3EAX, 5EAX, and 1EAX switches
- Western Electric No. 5 Crossbar switch.

Switching systems included in the current EMP analysis are:

- 4ESS
- 5ESS.

These switch types are included in the present EMP analysis because of their importance in the carrier networks, their support of NCS technical initiatives (particularly, NETS), the evolutionary prevalence of their technologies, and the availability of applicable test data and analyses. ESS systems are of particular interest in this report because they are based on semiconductor components, which are more susceptible to electrical overstress than electromechanical components. The electromechanical predecessors to ESSs, such as stepby-step, panel, and cross-bar systems, are based on technologies that are generally considered to be robust to the effects of EMP.

The 4ESS switch is a large, solid state toll system. Its design includes the extensive use of large-scale integrated circuits. The 5ESS switch is a modern, entirely solid state system intended primarily for local switching applications. Its design also uses large-scale integrated circuits and incorporates fiber optic cables for interbay connections. Although the 4ESS switch has yet to be tested, an engineering analysis of its survivability is included because of the prevalence of the 4ESS in the PSN. The 5ESS switch has been the subject of exhaustive test and analysis; this report includes an analysis of the results of that test program.

3.3 TRANSMISSION

In NETS network designs, little emphasis has been placed on identifying the specific types of transmission facilities that will be used to support the system. In general, however, the intertoll facilities of interest to the NETS network are:

- Microwave systems (especially TD-2 and TD-3)
- L carrier sytems (particularly L4 and L5)
- Fiber optic systems
- T2 carrier systems.

Given technological trends in the short-haul transmission arena, the following systems should also have some importance in an overall NETS network:

- T1 carrier systems
- ON carrier systems (ON1 and ON2)
- N carrier systems
- Fiber optic systems
- Short-haul microwave systems.

The critical transmission facilities considered in the EMP effects analysis reported herein are:

- T1 carrier system
- FT3C multi-mode optical fiber system
- L4 and L5 analog coaxial cable system
- TD-2 microwave system.

These transmission facilities are included in the present EMP analysis because of their prevalence in the PSN and the availability of applicable test data. The digital T1 carrier system has been tested extensively for EMP effects, and is representative of the T carrier technology used for exchange area transmission. The digital FT3C system has also been tested for EMP effects, and is typical of the fiber optic technology used for trunk transmission. L carrier systems are used widely as intertoll facilities, and have been tested for EMP vulnerability. Microwave systems are applied to both intertoll and short-haul transmission constituting approximately 60 percent of all transmission capability in the existing public networks.

3.4 SIGNALING

Operation of a network of switches and underlying transmission facilities requires the use of control signals to indicate the status of particular circuits and to pass call information. Without signaling capabilities, effective use of surviving switching systems and transmission facilities would be impossible. In the present commercial networks, two kinds of interswitch signaling are predominantly used: per-trunk signaling and common channel signaling. The impact of each is discussed below.

3.4.1 Per-Trunk Signaling

Per-trunk signaling uses as the signaling medium the facilities over which voice is passed. Both the sending and receiving of call control information are performed by the switches at either end of the circuit. The survivability of per-trunk signaling is in direct relation to the survivability of the switches and trunks used for voice messages. In general, whenever a usable voice path that depends on per-trunk signaling is present, the requisite signaling capability will be present as well. At present, the local exchange plant relies predominantly on per-trunk signaling. Many smaller interexchange carriers also use this signaling scheme.

3.4.2 Common Channel Signaling

Common channel signaling (CCS) uses data links that may or may not be physically associated with actual voice paths. In the AT&T version of CCS, known as Common Channel Interoffice Signaling (CCIS), the signaling paths are quite distinct from the voice paths they control. The result is that working voice paths may not be usable due to the loss of the required CCS. This situation is exacerbated by the distribution of signaling control for CCIS in only a few Signal Transfer Points (STPs). By the mid-1990s, practically all routes within the AT&T toll network will be under the control of CCIS. Other interexchange carriers, however, will likely remain with per-trunk signaling schemes until economic factors force the consideration of CCS.

CCIS uses dedicated data links as well as existing transmission facilities to carry signaling information. Therefore, the survivability of the links in the CCIS network is similar to that of voice transmission facilities and the accompanying data links. The survivability of the CCIS system also depends on the survivability of the STPs, which are the nodes of the CCIS network. The STPs use electromechanical and integrated circuit technologies similar to those of the switching systems used for voice message traffic. Therefore, in many respects, the vulnerability of the STPs is similar to that of the switching systems described in Chapter 6.0.

3.5 SYNCHRONIZATION

Synchronization is necessary to maintain reliable transmission over digital facilities. Within the AT&T network, the Bell System Reference Frequency (BSRF) is distributed to switching systems supporting digital transmission based on a hierarchical plan. The reference frequency is generated by three extremely stable oscillators operating in parallel in an underground site in Hillsboro, Missouri.

The transmission network for the reference frequency uses the same transmission facilities that are used for transmitting voice signals; no transmission facilities are dedicated to synchronization. Therefore, the EMP vulnerability of the synchronization network transmission facilities is the same as that of the voice network. Extensive redundancy is used to preclude loss of synchronization due to the loss of a few links in network. Loss of a particular transmission facility can be covered by using other facilities that normally carry voice signals Operationally, nodes in the synchronization network use the reference frequency they receive (master) to synchronize their own oscillators (slaves). The output of the slave oscillators is then sent to the next level in the network. If a node receives no reference frequency, the slave oscillators maintain operation, thus acting as frequency references themselves. All transmissions that use only facilities that obtain their synchronization from slave oscillators (directly or indirectly) are unaffected by the loss of the BSRF. The oscillators presently used can operate many weeks without an update from their masters and still support communications without significant message loss. Each of these factors contributes to the survivability of synchronization functions.

4.0 CHARACTERIZING THE EFFECTS OF EMP

4.0 CHARACTERIZING THE EFFECTS OF EMP

An important step in the characterization of critical assets from an EMP perspective is the determination of EMP induced stress levels. This chapter identifies significant parameters affecting EMP responses of telecommunications assets and summarizes the expected stress levels.

In the approach taken here, the assets and the EMP threat are described generically, with emphasis on the external environment and its coupling to and through external equipments into a building. For convenience, the assets are associated with a set of zones and boundaries as shown in Exhibit 4-1.

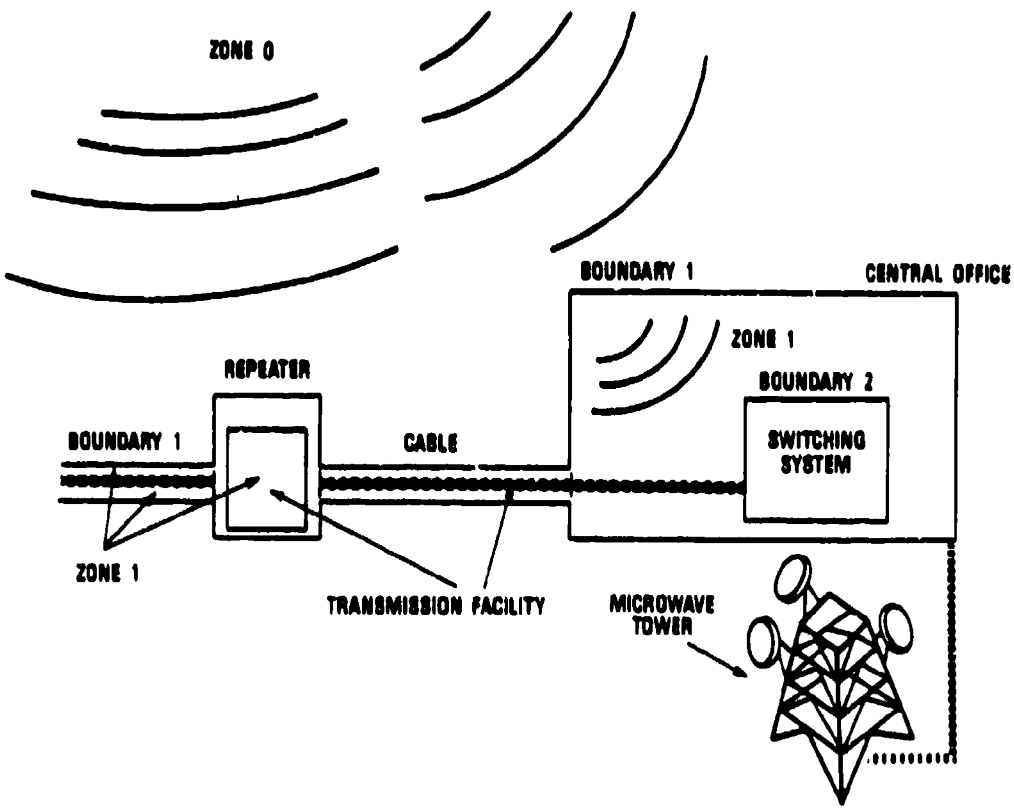


EXHIBIT 4-1. Zone-Boundary Model And Communications Network Elements.

This zone-boundary model is a representation of a telecommunications site from an EMP analysis perspective. The important features of the model relate to EMP coupling and attenuation as depicted in Exhibit 4-2. Note that one set of features shows conventional electromagnetic protection considerations; the other three sets are penetrations, shielding, and apertures.

The penetrations shown in Exhibit 4-2(a) are commonly found in PSN buildings. The power lines, communications cables, and microwave antennas are efficient electrical connections for conducting EMP into buildings. However, EMP can also couple significant energy through water pipes, gas pipes, and even sewer pipes. Since electrical surge effects from lightning, for example, are considered in the basic design of most telecommunications buildings, the analysis of these EMP penetrators must include the effectiveness of conventional protection.

The physical structures define an electromagnetic barrier. Exhibit 4-2(b) shows the various possible structural elements that could shield out EMP. Larger AT&T buildings typically have a steel I-beam frame. In cases where poured concrete construction is used, steel wire mesh or steel reinforcement bars (rebar) are often used. In the case of concrete block construction without the benefit of such reinforcement shielding, screens may be installed on the interior side of the walls. These items may be present as part of a radio frequency interference (RFI) shield. Another possibility is that certain rooms within the building may have shielding for interference protection. Once a picture of each structure's characteristics is developed, the EMP shielding of the structure is estimated.

In order to complete the description of EMP effects on a structure, the apertures, which are holes in the outer boundary, are identified. In Exhibit 4-2(c) the types of apertures normally encountered are shown. Doors, windows, and service access panels are obvious openings in the outer boundary. Vents and roof drains provide additional possible openings. There may also be holes from construction or changes and replacement of equipment.

The conventional EM protection perspective is represented in Exhibit 4-2(d). Conventional EM sources include surges (e.g., due to lightning) on incoming lines or unwanted EM fields (e.g., from radar) penetrating the building. The analogy with EMP is clear, and the conventional protection schemes used to counter these threats must be included in a representative model in order to perform the EMP evaluation of both the protection scheme and the facility response.

The remainder of this chapter contains a brief description of the EMP threat, estimates (stress levels) of the external coupling (boundary 1) to facilities, and the effects of conventional protection schemes and their EMP responses. In addition, a summary of some typical stress values induced on boundary 1 and boundary 2 by diffused fields (zone 1) is given.

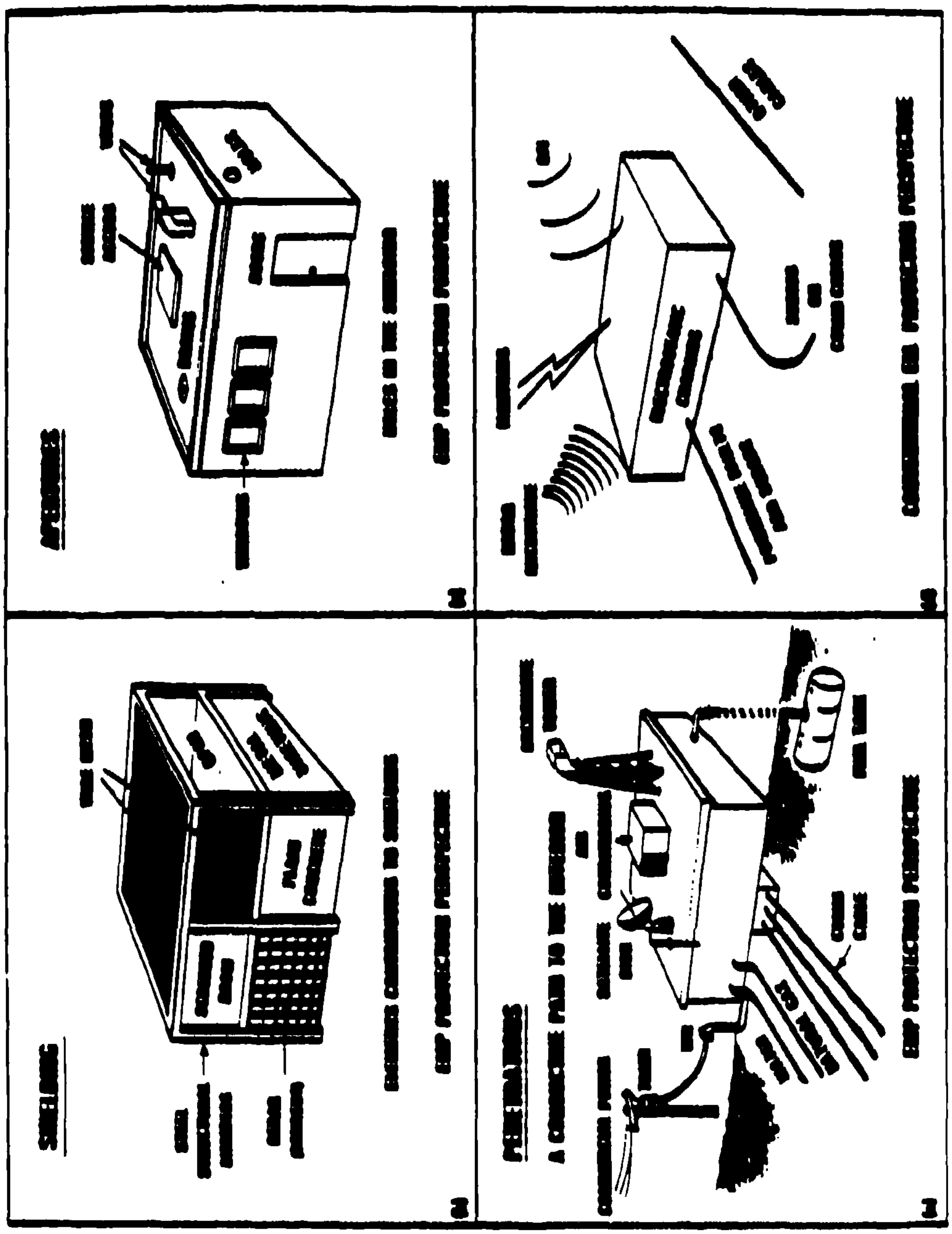


EXHIBIT 4-2. Important Features Of Central Offices From An EMP Perspective.

4.1 THE EMP THREAT

EMP is a phenomenon created by a nuclear explosion. It is a transient disturbance produced by exoatmospheric, atmospheric, and surface bursts and is characterized outside the source region chiefly by its short duration, high-intensity radiated electromagnetic field. This radiated field can cause severe disruption and possible damage to communications equipment. The most serious EMP threat is from an exoatmospheric or high-altitude burst of a large yield weapon that can illuminate a large portion of a communications network and simultaneously disrupt and damage communications equipment over a wide geographical user service area.

High altitude EMP, or HEMP, consists of three separate phases: the early-time portion, commonly referred to as early-time HEMP, arrives at the earth's surface very quickly and lasts about 1 μs. The second part of HEMP, sometimes called intermediate-time HEMP, occurs between times of 1 μs to 0.1 s. The third part of HEMP, called magnetohydrodynamic EMP or MHDEMP concerns electromagnetic disturbances lasting beyond 0.1 s (Ref. 2). It is the unclassified early-time HEMP (Ref. 1) from the high-altitude burst that is emphasized in this document since the EMP, blast, radiation, and thermal effects of air and surface bursts are only significant in negating geographically small communications functions.

Briefly, the early-time HEMP arises when the prompt gamma radiation from the high-altitude nuclear detonation ionizes the upper atmosphere. The ionized region radiates a transient electromagnetic pulse. The radiated fields on the earth's surface are intense and cover large geographic areas, making HEMP a general threat to electronic systems and networks. Three unique characteristics of HEMP distinguish it from other electrical/electromagnetic environments: the amplitude of the electric fields (on the order of 50 kV/m), the rise time of the fields (on the order of 10 ns), and the broadband frequency spectrum (0.1-100 MHz). The amplitudes of the electric fields are much larger than other EM radiation sources such as radar and radio frequency interference. The rise time is faster than most lightning strikes. The broadband frequency spectrum implies that facility elements not usually considered as "antennas" can collect significant energy.

Exhibit 4-3 is an unclassified representation of the electric and magnetic field time profiles and a frequency domain plot of the electric field from a high altitude nuclear explosion. This simplified description of the EMP threat indicates the features needed to identify the basic facility EMP characteristics, and provides for a composite of extremes, or the "worst case," for all parameters of importance (i.e., the shortest rise time, the longest fall time, and maximum amplitudes for both the vertical and horizontal polarizations). Refs. 1 and 4 provide additional descriptive and quantitative data for the EMP phenomenon the high-altitude burst.

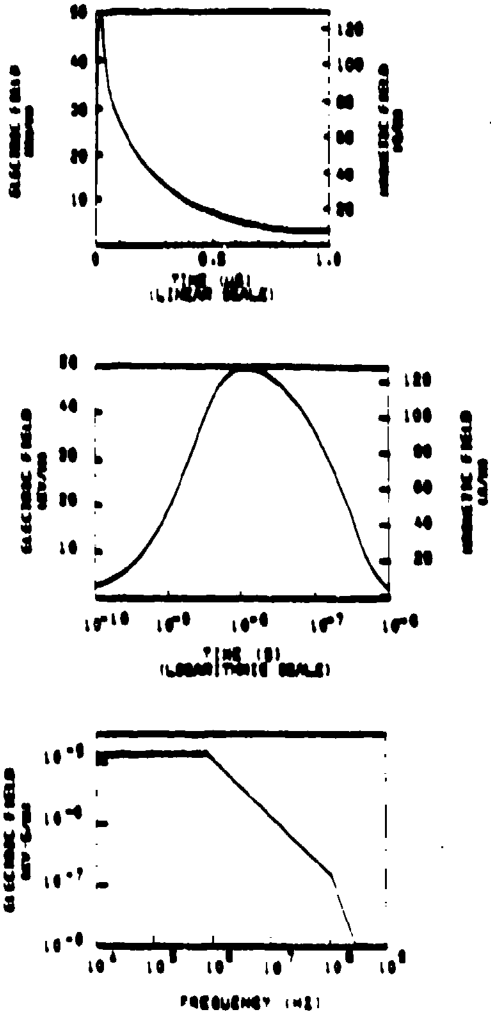


EXHIBIT 4-3. The HEMP Threat.

4.2 CABLE COUPLING

This section provides typical threat values for aerial, buried, and shielded cables as well as a description of the significant physical parameters that affect these values (e.g., polarization, angular incidence, soil conductivity, and cable depth and height). A more thorough analysis of long-cable (transmission line) pickup is given in Refs. 1, 5, 6.

A variety of factors influence the coupling of electromagnetic energy to long-line penetrating conductors. The EMP waveform characteristics such as magnitude, rate-of-rise, duration, and angle of arrival are important factors. Characteristics of the conductors are also important, e.g., conductor geometry (length, diameter, path terminations, distance above or below the earth's surface), conductor shielding, and conductor electrical properties (e.g., resistivity, inductance, capacitance per unit length).

4.2.1 Aerial Cables

The principal mode of EMP excitation using transmission line theory is the common mode signal between the cable(s) and ground. Exhibit 4-4 shows the coordinates used for this discussion.

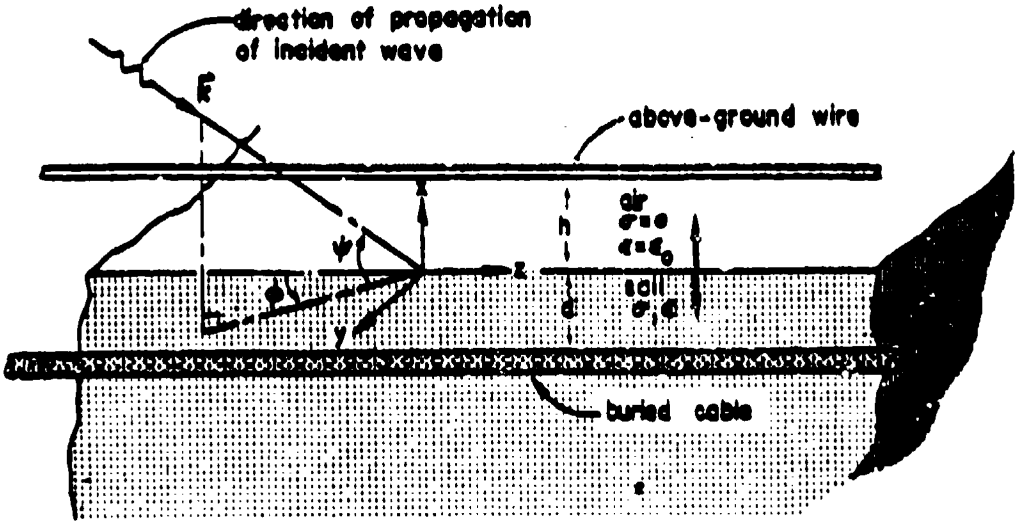


EXHIBIT 4-4. Coordinates For Angle Of Arrival Of Incident Wave.

To determine the common mode line voltages and currents produced on a given system, the values of the following parameters must be found: the common mode propagation constant (γ) and the characteristic surge impedance (Z_c), the common mode impedances at the terminations, and the distributed series voltage source function (V_i). The distributed series voltage source function (in V/m) is essentially the total longitudinal electric field (along the z direction in Exhibit 4-4) that results from electric and magnetic induction.

The characteristic impedance of a multiconductor line can be expressed in terms of the radius (a_e) of an equivalent single conductor at an average height (h) and as:

$$Z_c = \frac{Z_o}{2\pi} \ell n \frac{2h}{a_e}$$

where Z_0 = 377 ohms.

Losses in the conductor and ground must be taken into account for the propagation constant (γ). The propagation constant is given by

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)}$$

where $j = \sqrt{-1}$, ω = angular frequency and R, L, G, C are the distributed resistance, inductance, conductance, and capacitance per unit length. For perfectly conducting ground and a lossless line, $\gamma = j\omega\sqrt{LC}$. A more thorough comparison of the effects that the lossy and lossless propagation constants have on induced currents will be shown later in this section.

The open-circuit voltage or short-circuit current, together with the common mode line impedance, can be used to replace a transmission line with its Thevenin or Norton equivalent circuit. This can be used with the network representing the system beyond the transmission line terminals. Worst-case estimates can be based on the open- and short-circuit termination values. In addition, an incident common mode may excite other modes (differential) on the line because of multi-cable configuration and imbalances in the line-to-ground impedances.

The peak values of the induced transients are determined by sections of the line near the load end (critical line length) and, in many cases, are not influenced by the overall line length. That is, the critical line length (L_c), or the length of the line whose terminal response is the same as that of the semi-infinite line up to the time-of-peak, is given by

$$L_c = \frac{c\, T_p}{1 - \cos\psi \cos\phi}$$

where c is the speed of light and T_p is the time-to-peak. The angles of incidence are shown in Exhibit 4-4 with respect to the $\vec{k}$ vector of the plane wave EMP and the cable direction. It should be noted that the transmission line approach used here is valid when the cable height (h) is small compared to the wavelength of the radiation, although the method gives surprisingly good results even when this condition is not satisfied.

The transmission line acts as an integrating network for both the directly incident and ground-reflected waveforms. The polarizations are defined such that the incident electric field vector is parallel to the air/soil interface for horizontal polarization, and for vertical polarization the electric field vector lies in the plane containing $\vec{k}$ and a line perpendicular to the air/soil interface.

Exhibit 4-5 shows the time dependence of the current on an overhead line in a parametric fashion so that estimates of the current can be made as a function of the soil conductivity (σ), incident pulse shape ($E_0 e^{-t/\tau}$), and characteristic impedance (Z_c) for both vertical and horizontal polarizations. For calculational convenience, the peak current induced at the end of a lossless cable over an infinitely conducting soil by the incident pulse shape is on the order of

$$I_{pk} = \frac{E_0 2h \sin\Psi}{Z_c} D_{H,V}(\Psi,\phi)$$

where the angular dependence (directivity) is approximately

$$D_H = \frac{\sin\phi}{1 - \cos\Psi\cos\phi} \quad \text{for horizontal polarization}$$

and

$$D_V = \frac{\cos\phi\cos\Psi}{1 - \cos\Psi\cos\phi} \quad \text{for vertical polarization.}$$

For example, a response for a typical pulse width (τ = 100 ns) and ground conductivity ($\sigma = 10^{-2}$ mhos) is shown in the curve labeled $\sigma\tau = 10^{-9}$ at $\psi = 30°$, $\phi = 0°$.

The determination of induced current in lossy transmission lines with the inclusion of the frequency dependence of the propagation constant and both the frequency and angular dependence of the reflection and transmission coefficients of the electric field at the air/soil interface requires a numerical integration (Ref. 1). Exhibit 4-6 shows the result of a numerical evaluation for both polarizations. In the exhibit, the peak voltage versus angle of incidence for maximum directivity is shown for characteristic soil conductivities, and a comparison is made with the lossless transmission cable at a line height of 10 m.

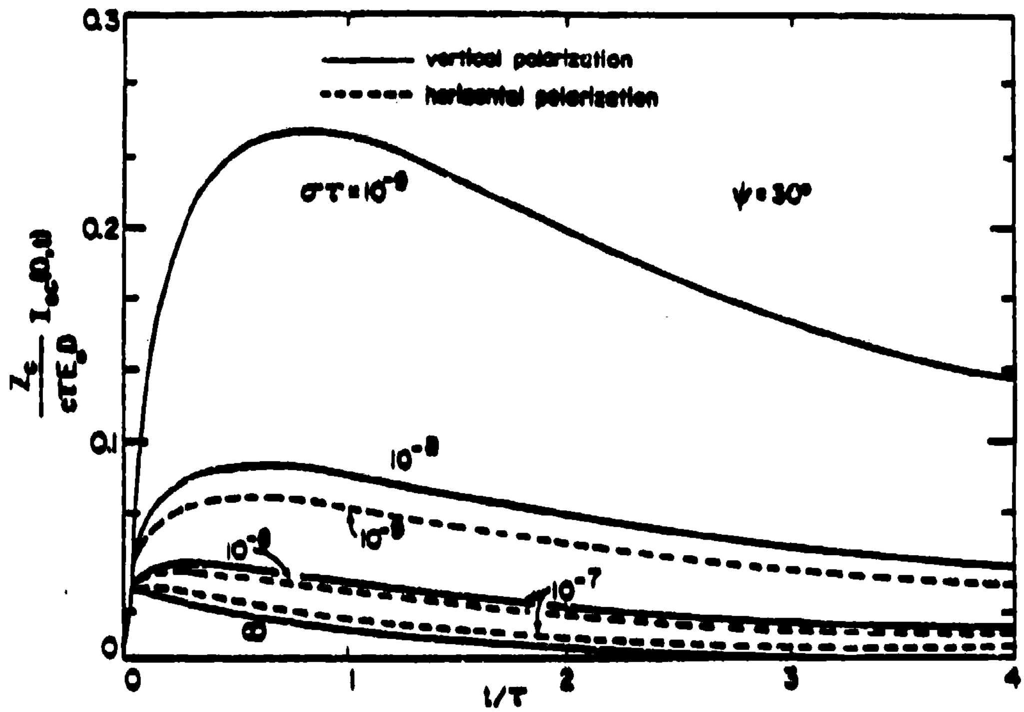
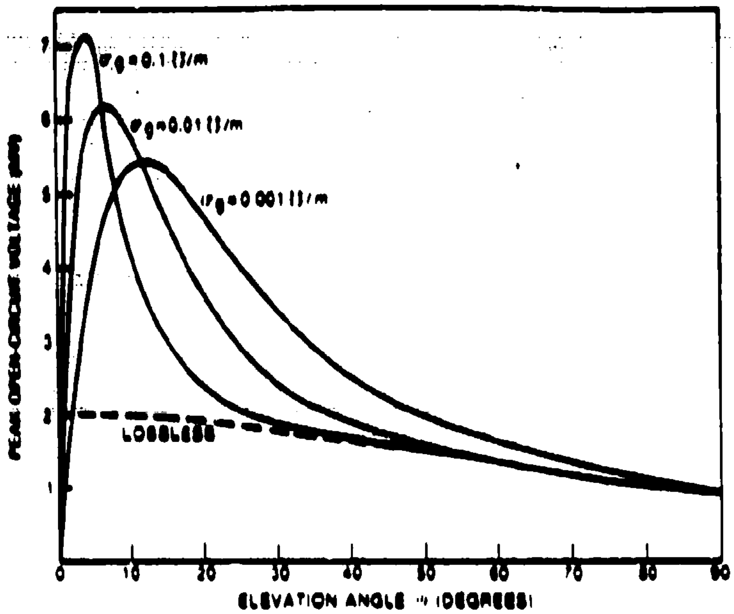


EXHIBIT 4-5. Short-Circuit Current Induced At The End Of A Semi-Infinite Serial Wire By An Exponential Pulse.

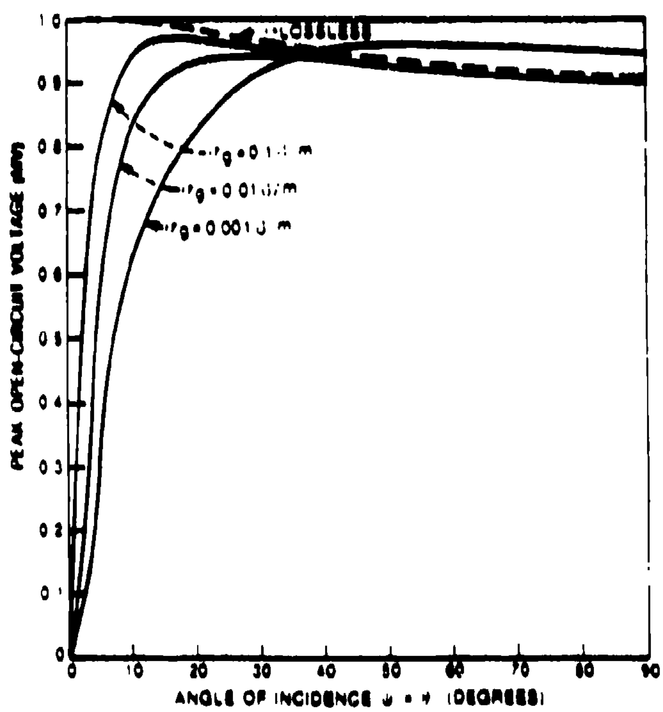
For vertical polarization at a given elevation angle (ψ), maximum coupling to the line occurs for incidence near the vertical plane containing the X axis and the cable ($\phi = 0°$). Compared with the lossless response, there is an enhancement of the open-circuit voltage. This is due to the partial reflection of the electric field vector from the imperfect ground plane. At broadside incidence ($\psi = 90°$), the magnitude of the reflection coefficient is nearly 1 and its phase is near 0, so that the open-circuit voltage response is nearly equal to that of the lossless line.

As the angle of elevation decreases, the magnitude of V_{oc} increases due to the rapid decrease in both the magnitude and phase of the reflection coefficient. This behavior continues until small angles of incidence are reached, where the critical line length rapidly increases and line loss dominates, which suppresses any voltage accumulation.

The maximum response for horizontal polarization is obtained when the angle of incidence for elevation and azimuth are equal ($\psi = \phi$). For this polarization as compared to the vertical polarization, the magnitude and phase of the reflection coefficient do not vary significantly with elevation angle over the frequency range in question. As a result, it is similar to the lossless case except where the line loss dominates at the smaller angles (< 20°). Exhibit 4-7 summarizes the peak voltage, peak current, time-to-peak, and critical length of line, as well as the angle of incidence for which these maxima occur for both polarizations for a typical line 10 m high with Z_c=500 ohms.



(a) Vertical Polarization



(b) Horizontal Polarization

EXHIBIT 4-6. Lossy Line Peak Open-Circuit Voltage vs. Elevation Angle.

	EARTH CONDUCTIVITY σ_g (Ω/m)	MXIMUM PEAK OPEN-CIRCUIT VOLTAGE V_{oc} (MV)	MAXIMUM PEAK SHORT-CIRCUIT CURRENT I_{sc} (kA)	TIME TO PEAK t_p (ns)	CRITICAL LENGTH OF LINE L_c (km)	ANGLE OF INCIDENCE ψ (DEGREES)
[illegible]	0.001	0.96	1.9	180	0.092	($\phi = \psi$) 50
	0.01	0.94	1.88	40	0.087	25
	0.1	0.96	1.9	20	0.14	12
	∞	1.0	2.0	10	∞	0
Vertical Polarization	0.001	5.4	10.8	270	3.7	($\phi = 0$) 12
	0.01	6.2	12.4	140	7.8	6
	0.1	7.25	14.5	90	10	4
	∞	2.0	4.0	90	∞	0

EXHIBIT 4-7. HEMP-Induced Transients On A Powerline ($Z_C = 500\,\Omega$, h = 10 m).

4.2.2 Buried Cables

The earth is generally characterized as a fair conductor for calculation of the reflected field above the air-ground interface. However, the ground plane really has a diffuse thickness proportional to the skin depth of the soil. For the frequencies of interest in the EMP spectrum, the skin depths range up to several meters in depth.

The imperfect reflection of an EM wave on the air/soil interface results in partial transmission of the longitudinal field component (along the cable), which acts as a distributed voltage source function. The characteristic soil impedance Z_s in this environment is different from the aerial case due to the difference in soil permittivity (ϵ) and conductivity (σ). For most practical cases, the soil impedance per unit length of a buried cable is given by

$$Z_C = \frac{j\omega\,\mu_0}{2\pi}\ \ln\left(\frac{\sqrt{2}\ \delta}{1.8\ a}\right) = j\omega L_s$$

where a is the conductor radius, δ is the skin depth, and μ_0 is the permeability of free space.

The propagation constant for the buried transmission line (with the surrounding soil as a return conductor) for most practical cases has a magnitude that is inversely proportional to the skin depth

$$\gamma = \frac{(1+j)}{\delta} = (1+j)\sqrt{\frac{\omega\mu_0\sigma}{2}}$$

where σ is the ground conductivity.

The peak short-circuit current for a surface cable is given by the approximation

$$I_{pk} = 8.1 \times 10^5 \frac{E_0\sqrt{\epsilon_0 \tau}}{\sqrt{\sigma}} D_{H,V}(\psi, \phi)$$

where

$D_H = \sin\psi \sin\phi$, for horizontal polarization

and

$D_V = \cos\phi$, for vertical polarization.

Exhibit 4-8 shows the parametric dependence of the induced cable current as a function of time. The parameter for the depth of burial (d in meters) is given by

$$p = \frac{\tau_d}{4\tau} = \frac{\mu_0\sigma\, d^2}{4\tau}$$

where the constants μ_0 , σ , τ are defined as in Section 4.2.1 on aerial cables. For example, for the curve p=0.1, $\sigma = 10^{-2}$ mhos, and τ =250 ns, the depth of burial is 1 m (d=1) and for p=0.1, d=3 m. The time-to-peak for depths of 0 to 3 m is about 0.85 τ or 200 ns for τ =250 ns. The increase in rise times with the increase in cable depths is indicative of the shielding effect that the ground has on the high-frequency components of the incident spectrum.

Exhibit 4-9 depicts the angular coupling $D_{H,V}$ for each polarization. Comparing these dependencies with the aerial case (Exhibit 4-7), it can be seen that the peak-induced signal strength for vertical polarization is more sensitive to the elevation angle (ψ) for an overhead line as opposed to a buried line. For horizontal polarization, the peak signal strength of the buried cable is more affected by ϕ than the aerial line.

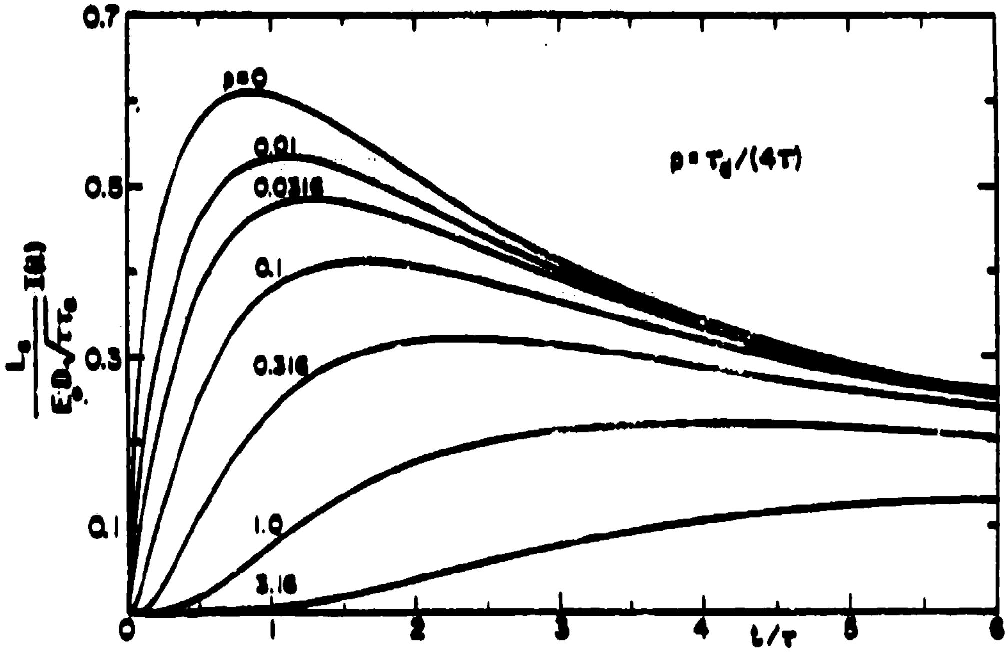


EXHIBIT 4-8. Normalized HEMP-Induced Waveform On Long Buried Cables.

Numerical evaluations of the induced currents with the inclusion of the impedance and propagation variations on skin depth and frequency, as well as the angular and frequency dependence of the transmission coefficients, resulted in maximum threat levels of 2 kA with rise times on the order of 200 ns. The critical line length for buried cables is expressed as

$$L_C = 10^8 \frac{\sqrt{\epsilon_0 \tau}}{\sqrt{\sigma}} \qquad \text{for bare cable}$$

and

$$L_C = 5 \times 10^8 \sqrt{\frac{\log b/a}{10\epsilon_r}} \qquad \text{for insulated cable}$$

where a is the radius of the conductor, b is the thickness of the insulation, and ϵ_r is the dielectric constant of the insulation. For typical parameters given above, the critical line length is on the order of 15 to 30 m.

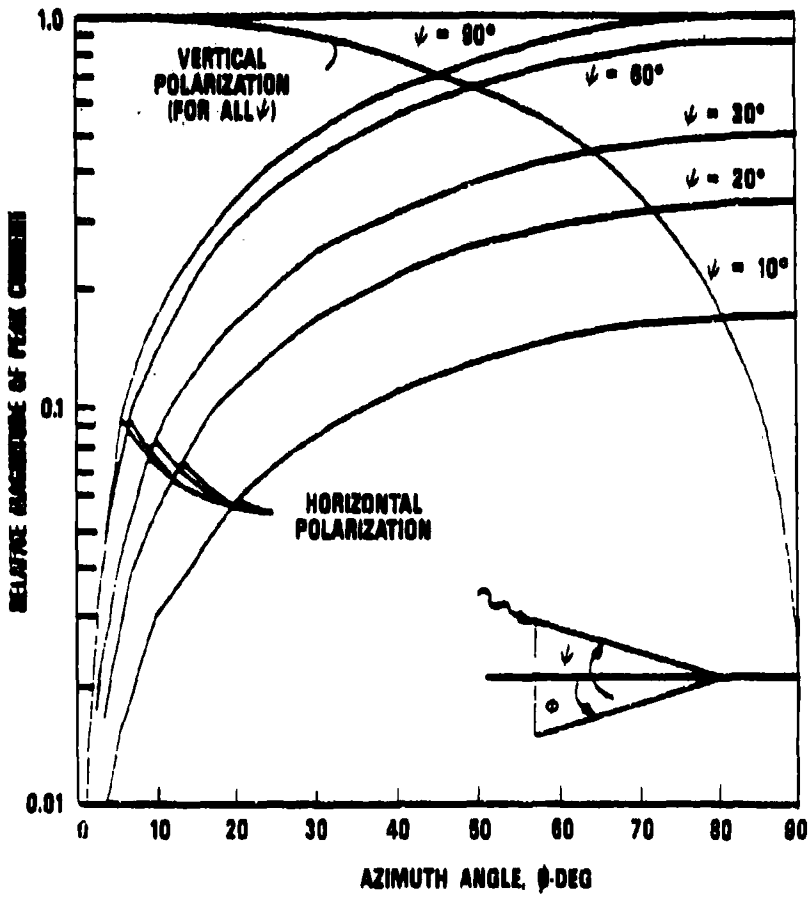


EXHIBIT 4-9. Relative Amplitude For Peak Induced Current On Buried Conductors.

4.2.3 Vertical Risers

A vertically polarized EMP will induce currents in vertical conducting components of service entrance conduits (e.g., downleads from power and communication lines) or in conductive structures such as radio towers, waveguides, and cables to overhead antennas. For horizontally polarized waves, the vertical elements behave as passive impedances with delay times associated with their lengths. The vertical element is treated as a transmission line with its upper-end terminated in impedances appropriate to the physical system.

The current induced in a downlead from an overhead power line is shown in Exhibit 4-10. In this example the line is short and the angle of incidence is 30° or 0°. The peak current is limited by the line height in this example; for taller structures, the leading edge of the current wave will continue to rise as the integral of the incident wave (towers are discussed in Section 4.2.4). The induced current will increase with structure height for structures up to a few hundred feet high. The parameters used in Exhibit 4-10 are the same as described in Sections 4.2.1 and 4.2.2.

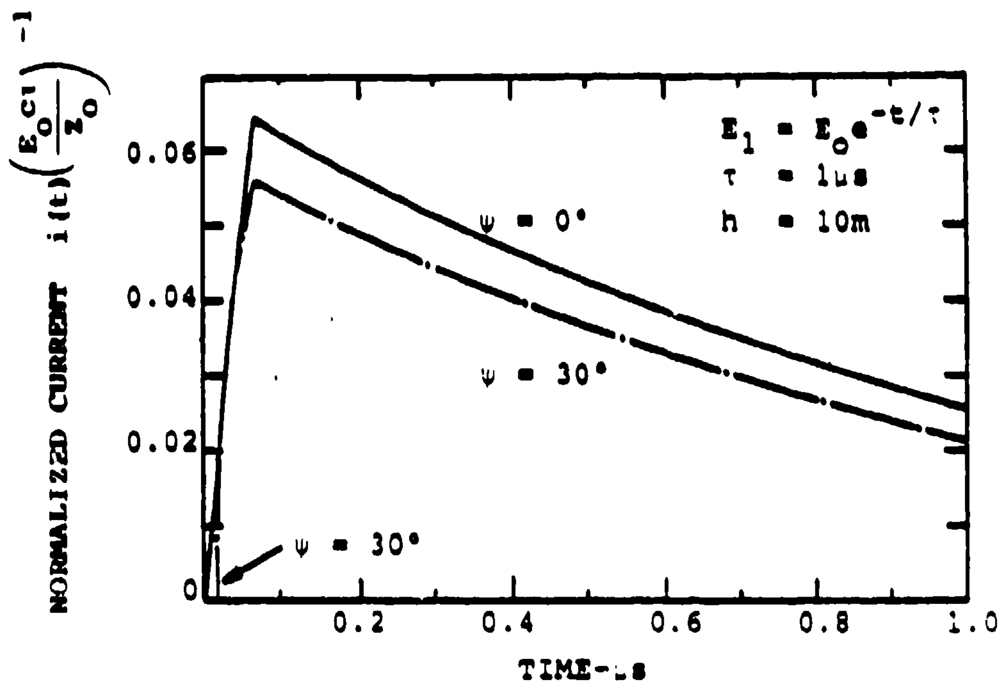


EXHIBIT 4-10. Induced Current At The Base Of A Vertical Riser By A Vertically Polarized Incident Wave.

The current waveform shown is that induced in the vertical element only; this current must be added to any current induced in the horizontal line (by a vertically polarized incident field) with proper regard for time delays. The total current induced is dependent on the reflection coefficient at the base of the vertical riser, the transit time from the base to the top, and the angle of incidence of the vertically polarized field. For grazing incidence, $\psi = 0°$ and $\phi = 90°$, the vertical riser current can be larger than the horizontal line current. Further detailed evaluation of the current waveforms resulting from vertical risers and horizontal run can be found in Ref. 8.

4.2.4 Microwave Tower/Waveguide Coupling

Long-haul transmission systems frequently use line-of-sight microwave radio. A structural steel tower at each junction in the system generally supports the microwave antennas. These towers usually range in height from 30 to 130 m. Exhibit 4-11(a) shows the typical method for connecting the waveguide to the antenna tower and grounding the tower. To protect the structure and equipment from lightning transients, the entire tower/waveguide structure (tower, waveguide, raceway, and ac conduits) is well-bonded to the station's ground.

Both vertical and horizontal components of a HEMP transient can effectively couple to this system. Most of the induced current follows the low impedance path formed by the tower legs and external ring ground, although some current enters the building via the waveguides and ac conduits. Analytical models to predict the induced currents on the tower and waveguide are extremely complex and the results are uncertain. Consequently, estimates are based on simulation testing and scale model (Refs. 9, 10, 11, and 12) tests. For purposes of initial estimates, the system can be modeled as a fat monopole above a ground plane (see Exhibit 4-11(b)) or a fat dipole with a half-height equal to the height of the tower.

The expected response of the dipole to a broadband pulse is a damped sinusoid with a ringing frequency around $f_o = 75/h$ MHz where h is the tower height in meters. The amplitude of the induced current is proportional to the tower height and width (or fatness). As the width increases, though, the induced signal has a broader bandwidth and lower Q (damps out more quickly). Exhibit 4-12 can be used to determine minimum and maximum peak currents on the tower as a function of the fatness factor $\Omega_t = 2 \ln 2h/a_e$, where h is the tower height and a_e is the equivalent dipole radius. The ordinate value is in ampères per foot, so multiplying by the tower height gives the peak current in amps. The lower limit of Ω_t (maximum current) is assumed to be the radius of a circle circumscribing the tower base. The upper limit of Ω_t (minimum current) is based on the effective radius of a single waveguide descending the tower from the microwave antenna.

The distribution of induced currents that do not follow the low impedance path from tower to ground results in half of the induced current traveling over the waveguide and half over the ac conduits. The maximum tower current from the vertically polarized field is about 11 kA peak-to-peak and the maximum peak-to-peak current from a horizontally polarized field is 3.5 kA. This results in about a 6 kA peak-to-peak current on the waveguide.

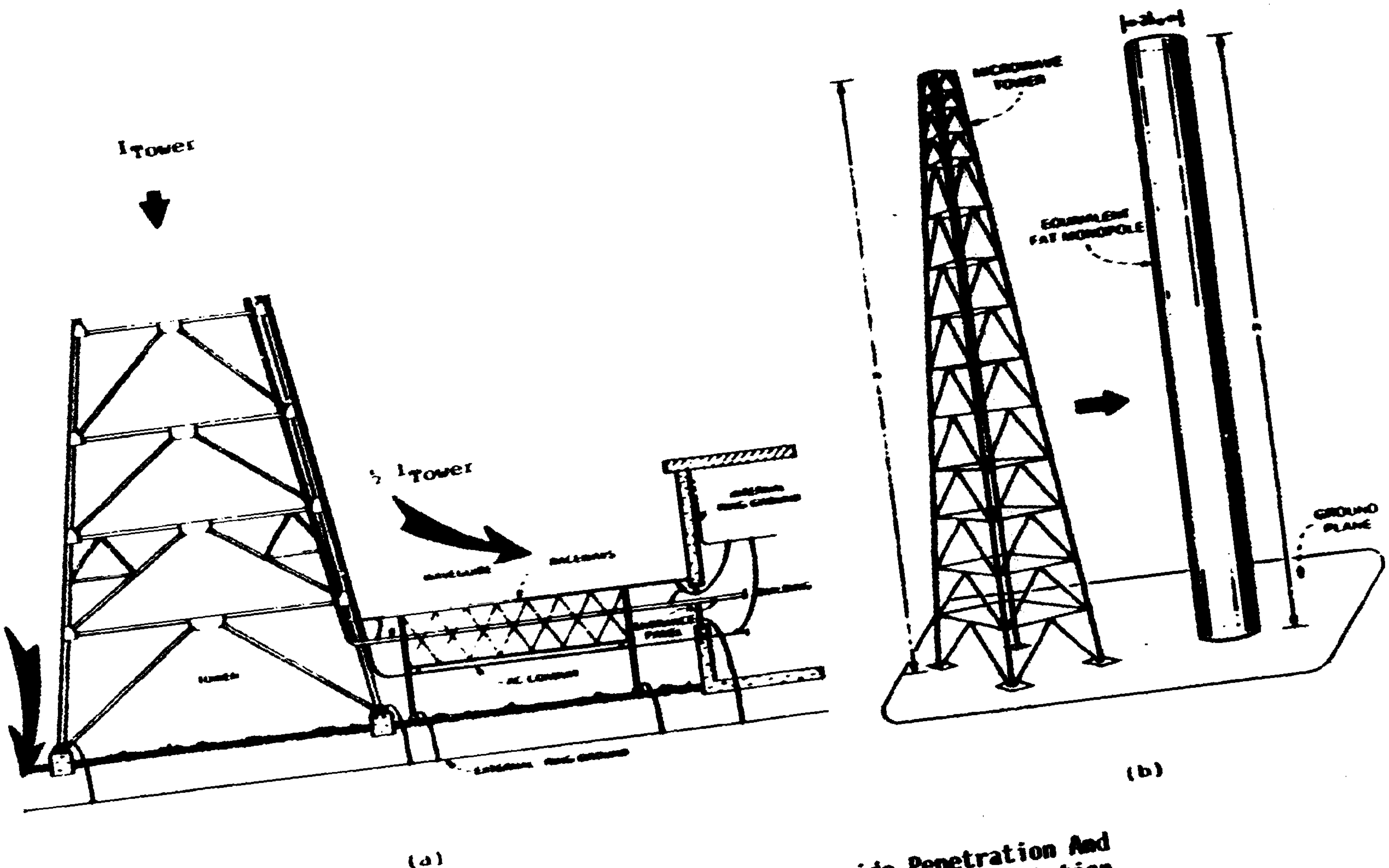


EXHIBIT 4-11. Tower/Waveguide Penetration And Tower Analytical Representation.

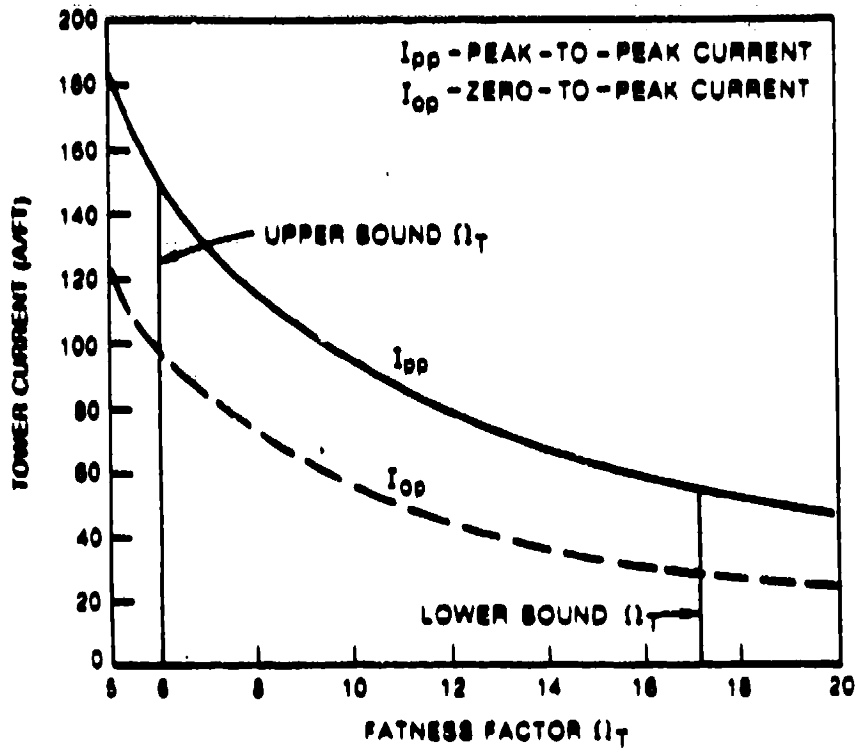


EXHIBIT 4-12. Peak Tower Current vs. Fatness Factor.

4.3 DIRECT ILLUMINATION

Direct illumination threat values given here refer to exposure to an incident EMP field without consideration of the contributions from conducting penetrators. This direct illumination exposure results from the free field interaction with the ground as well as the penetration through walls, roof, doors, windows, and other apertures.

As a result of this mode of penetration, internal induced signals will be dependent on the internal cable lengths, terminations, and building construction. No simple single model exists for predicting the induced transient level for these complex situations. However, site-specific geometric and cable arrangements can be modeled for analytic purposes, or EMP simulator testing can be used to determine internal signal levels. The results from previous analyses and tests can then be used to develop order-of-magnitude estimates of the internal induced stresses.

A data base has been developed for determining the signal levels from direct illumination in essentially unshielded operational facilities through test programs (Refs. 11, 12, and 13) over the last several years. These tests examined the effects of angular incidence and building construction on signals induced on interbay (internal) wiring. The tests have shown that measured currents induced on interbay wiring can be characterized as the sum of several damped sinusoidal transients. Exhibit 4-13 shows the typical ranges of parameters such as ringing frequencies (f_o), damping factor ($t_{1/e}$), and 95 percentile peak amplitude current in amps. The ranges did not vary significantly from site to site. Also, the e-folding time (decay time) was not strongly dependent on the ringing frequency.

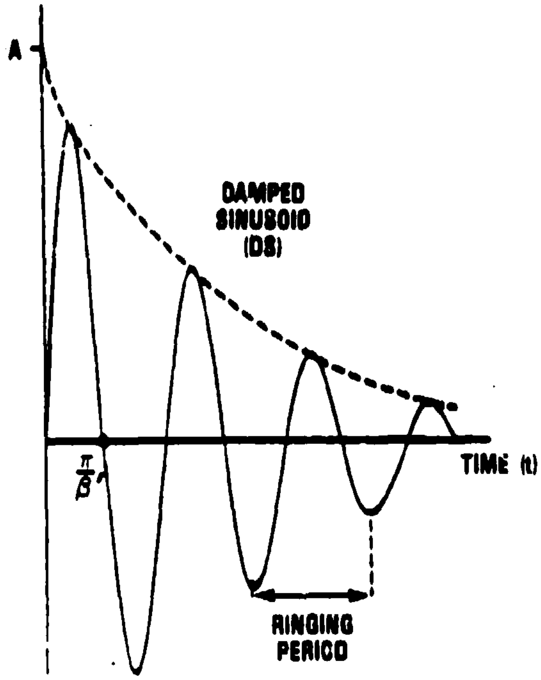
			Peak-to-Peak Current (Amps)	
			Type of Building	
	f_o(MHz)	$t_{1/e}$(s)	Concrete Block	Poured in Place
Average	7.2	4.6	10.0	0.3
Median	6.3	4.3	6.0	0.3
Range	1-16	1-8	3-20	0.2-5.0

EXHIBIT 4-13. Induced Current Waveforms From Direct Illumination.

Exhibit 4-14 shows an example of the waveform that represents an internally coupled damped signal S(t). The damped signals are the result of reflections, interbay inductances, and capacitances present within the wiring distribution.

4.4 BOUNDARY 1 PRACTICES AND EFFECTS

This section covers boundary 1 characteristics and practices that partially mitigate and alter the conducted and illumination stresses. These include cable and building shields, shield terminations, bonds and grounding paths, transient protection, and filters. Each is discussed with respect to present and potential applications in the PSN. This section details the basics of boundary 1 transient mitigation techniques and estimates expected stress levels radiated and conducted through the boundary to zone 1 and boundary 2 of generic network sites.



COUPLED

$$S(t) = Ae^{-a't}\sin \beta' t \text{ [VOLTS, AMPS]}$$

A = AMPLITUDE

a' = DECAY CONSTANT

β' = RINGING FREQUENCY

EXHIBIT 4-14. Typical Damped Sinusoid Waveform.

4.4.1 Shielding Principles

Shielding plays a principal part in HEMP mitigation. In shielding practice, a distinction is made between cable and volume shielding. Cable shields provide a path (the shield) for induced or coupled EMP current, other than the signal or power wire itself.

Volume shielding is electromagnetic isolation of conductors or volumes from one another. Shields are thought of as impervious barriers with imperfections. In a building in the PSN, the first layer, or boundary 1, is the building structure. For exposed cables, the first layer is the sheath that surrounds the signal lines.

Shields can mitigate electric (E) and magnetic (H) fields. For E-field shielding, the requirement that the shield be continuous, or closed, is of paramount importance (Faraday's Law). For H-field shielding, current must flow over the shield; the shield must provide a low-impedance path (Lenz's law). Important properties for attenuation are conductivity, thickness, and permeability.

Shielding action is unchanged when shields are grounded, since the relation between current on the shield and field in the shield depends strictly on the shield transfer impedance, independent of grounding. However, shields should be grounded for safety or to minimize reflections when large induced sheath currents are expected.

Some important parameters in the discussion of shielding are shielding effectiveness and transfer impedance. The definition of shielding effectiveness (SE), in decibel units, as a relation between the fields exterior and interior to the shielded volume is defined as follows:

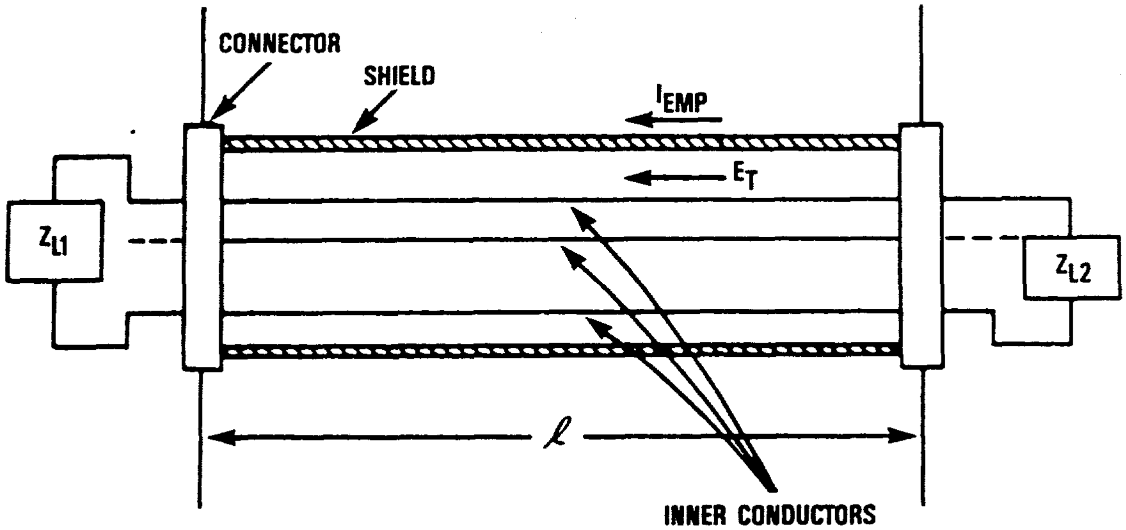
$$SE(dB) = 20 \log_{10} \left[\frac{\text{FIELD AMPLITUDE (EXTERIOR)}}{\text{FIELD AMPLITUDE (INTERIOR)}} \right]$$

This is used in volume shielding (e.g., the change in field strength after passing through walls of a building).

Transfer impedance, when multiplied by the current that EMP has induced on a shield, provides the voltage developed inside the shield with respect to shield ground. The smaller the transfer impedance, the more effective the shield is in reducing induced voltage or current. The current that then flows on the inner conductors is a function of the characteristic impedance of the inner conductors and of the electrical loads on both ends of the cable. For cable shields, the transfer impedance gives a more useful measure of shielding than shielding effectiveness based on the ratio of shielded-to-unshielded current.

The determination of transients induced onto cables by EMP typically involves two calculations: the calculation of coupling onto the sheath (i.e., Section 4.2) and the calculation of the voltage induced on the internal wires. The calculation of coupling onto the cable sheath depends on cable construction and location, and will be discussed for some typical cases in Section 4.4.3. Exhibit 4-15 illustrates the calculation of voltage induced on a wire within a shielded cable.

Also important is the skin depth, which is a measure of the depth to which currents penetrate in a conductor. Skin depth, δ, is a function of frequency, conductivity, and permeability. An even more significant parameter is T/δ, the ratio between shield thickness and skin depth. A rule of thumb is that good shielding will result if $T/\delta > 1$; the curve of attenuation as a function of T/δ shows significant reduction at $T/\delta = 3$ and drops off logarithmically for lower values of T/δ.



$$Z_T\ (W) = \vec{E_T}\ (W)\ /\ I_{EMP}\ (W)$$

- **FOR A CABLE BRAID, Z_T HAS UNITS OF OHMS/M**
- **FOR A CONNECTOR, Z_T HAS UNITS OF OHMS**

$$\Delta V = I_{EMP} Z_T \ell$$

ΔV = **VOLTAGE DROP ON CENTER CONDUCTOR OF CABLE OF LENGTH**
I_{EMP} = **SHEATH CURRENT**
Z_T = **TRANSFER IMPEDANCE PER UNIT LENGTH**
ℓ = **INCREMENTAL LENGTH**

EXHIBIT 4-15. Cable Shield Transfer Impedance Calculation.

Field wavelength is an important variable in shielding predictions. When field wavelength is smaller than or approaches the size of apertures, holes, or discontinuities in a shield, the SE is reduced dramatically. When the wavelength approaches unshielded wire lengths or shield lengths, ringing or resonance can alter the SE by orders of magnitude. In addition, when the wavelength of the H field approaches the dimensions of the shield, grounding of the shield is important, so that induced current has a circuitous path or so that current reflections on the shield are reduced.

4.4.2 Building Shielding

Volume shielding may exist as a natural consequence of building construction, or it may be a design feature. EMP hardening usually includes shielding at the building level, but all buildings already provide some protection depending on the amount of structural metal. Generally, buildings designed to withstand up to 0.5 psi overpressure are made of concrete block or thin precast panels that contain some steel bars and some steel mesh between courses of block to enhance strength. They may provide up to 10 dB of SE. Often, some extra construction procedures can enhance the shielding effectiveness of an ordinary building. Shielding materials provide good attenuation, so SE is primarily a function of imperfections, penetrations, and their treatment. Construction and installation methods notably affect shield integrity.

Buildings designed (Ref. 1) to withstand at least 2 psi of overpressure have reinforced walls that can be "poured-in-place" or "precast tilt-up." In poured-in-place walls, steel reinforcing bars (rebar) or mesh are erected first, and concrete is then poured into temporary forms surrounding the metal structure. Some buildings are built with full coverage bonded mesh or rebar (integral shielding), in which the metal overlaps and is tied or (preferably) welded with steel wire providing a significant electrical interconnection. The shielding effectiveness for this design may be from 30 to 50 dB. Other buildings have bonded metal sheet on all six sides inside the building. The latter construction is used when EMP protection is a design maxim, and is also often used for EMI or TEMPEST protection.

Some problems that compromise building shielding integrity are apertures and other discontinuities. Apertures can be windows, entrances, vents, etc. Other discontinuities include seams, cracks, corners, and construction interfaces. These features pose two problems: direct illumination may penetrate through open spaces or force them to oscillate like radiating antennas, and current flow on a surface will radiate when it crosses a discontinuity. External fields diffuse through an aperture better with increasing frequency; experimentally this is seen to begin when the wavelength is within one or two orders of magnitude of aperture dimension. Protection techniques might include waveguide honeycombs on vents, bonded screens on windows, or RF door frames. Additionally, low-impedance paths protect against radiation from induced currents. This radiation is produced by changes in vector current density; variations in magnitude (as in a pulse) or in direction of flow (as around an aperture).

Some common examples of these problems are coupling to wires that pass near windows, increases in measured field levels near a spot-welded seam or door frame, and field enhancement in corners. One fact in common with all of these problems is that they are difficult, if not impossible, to predict quantitatively. Indeed, a quantitative study of aperture and seam diffusion and radiation could only be accomplished on a site-by-site basis, supported by testing. More detail about building wall construction methods are presented here with data from experimental tests of the SE of some buildings in the PSN.

In the PSN, few buildings have continuous metal volume shields. Some telephone central office (CO) buildings are brick and block, and some others in metropolitan areas are intentionally shielded using good construction techniques. A requirement (Ref. 14) exists to provide building shielding where existing or expected RFI levels exceed 2 V/m between 500 kHz and 1 GHz. However, these levels, generated by radio stations and weather and airport radar, are very low compared with expected HEMP fields.

Tests on an unshielded poured-in-place concrete building with telephone equipment showed E fields reduced by 25-35 dB and H fields reduced by 5-15 dB up to 1 MHz. Testing was done up to 100 MHz and no shielding was seen above 1 MHz (Ref. 14). Most unshielded buildings are even less effective. Better levels can be achieved with a small amount of shielding, which is more common.

Materials used for shielding commercial buildings are soldered bronze or copper screens, bolted or welded galvanized steel rods or sheets, and bolted copper or silicon steel sheets (Ref. 15). Welded galvanized wire mesh is the best non-sheet shield against RFI; the spectrum shielded depends on mesh spacing, but 100 MHz is about the highest shielded frequency for 12-inch spacing mesh with window and door frames bonded to the mesh. For closer spacing, a one-quarter-inch mesh, for example, can be efficient into the 500 MHz range (Ref. 14). At another PSN site (Ref. 14), a building with precast concrete and a bonded wire mesh was measured to offer 20 to 40 dB for E field SE and 0-20 dB for H field SE from 10 kHz to 100 MHz. For comparison, a poured-in-place concrete PSN building with tied rebar was tested to provide 45 to 55 dB E-field attenuation and 20 to 35 dB H-field attenuation up to 1 MHz, with no attenuation at higher frequencies. These PSN test results illustrate an accepted tenet: bonded rebar can provide good shielding, but shielding conductors must be tightly spaced, like a mesh, to be effective at higher frequencies.

Metal sheet shields, of course, can be expected to offer more protection. Sheets are thicker than cable shields (a couple of millimeters) for structural soundness and prevention of corrosion. Effectiveness depends upon treatment of penetrations. A reasonable expectation is 60 dB of shielding; 120 dB has been measured for some shields at some frequencies (Refs. 15, 16). Occasionally, buildings are buried, which adds to shielding effectiveness.

4.4.3 Cable Shielding

Cable shields (boundary 1) are used for long communication lines and internal wires inside buildings in the PSN. The following discussion concerns the use of shields and various types, their termination practices, and their transfer impedances.

EMC or TEMPEST requirements often dictate shielding of power, signal, and control lines. Attenuation of radiated narrowband and broadband high-frequency and spurious noise, and occasionally, attenuation of radiated electrostatic or low-frequency fields, motivate shielding in these cases. Another motivation is lightning effects: shields conduct large induced or injected currents, and attenuate broadband high-frequency radiated fields that result from induced currents on nearby conductors. A myriad of materials are used for cable shields. Some examples are copper, aluminum, steel, nickel, and various alloys and platings.

On the basis of their shielding characteristics, practical cable shields may be separated into two categories: tubular (solid) shields that contain no apertures, cracks, or slits, and all other shields that contain such imperfections. Tubular shields, such as extruded lead sheaths and rigid steel conduit (with tight couplings), will strongly attenuate high frequencies. Above the frequency at which the wall thickness is one skin depth (typically greater than 1 MHz), the attenuation is large and increases almost exponentially as the frequency increases. In addition, tubular shields minimize leakage capacitance between the internal conductors and the external shield-return circuit.

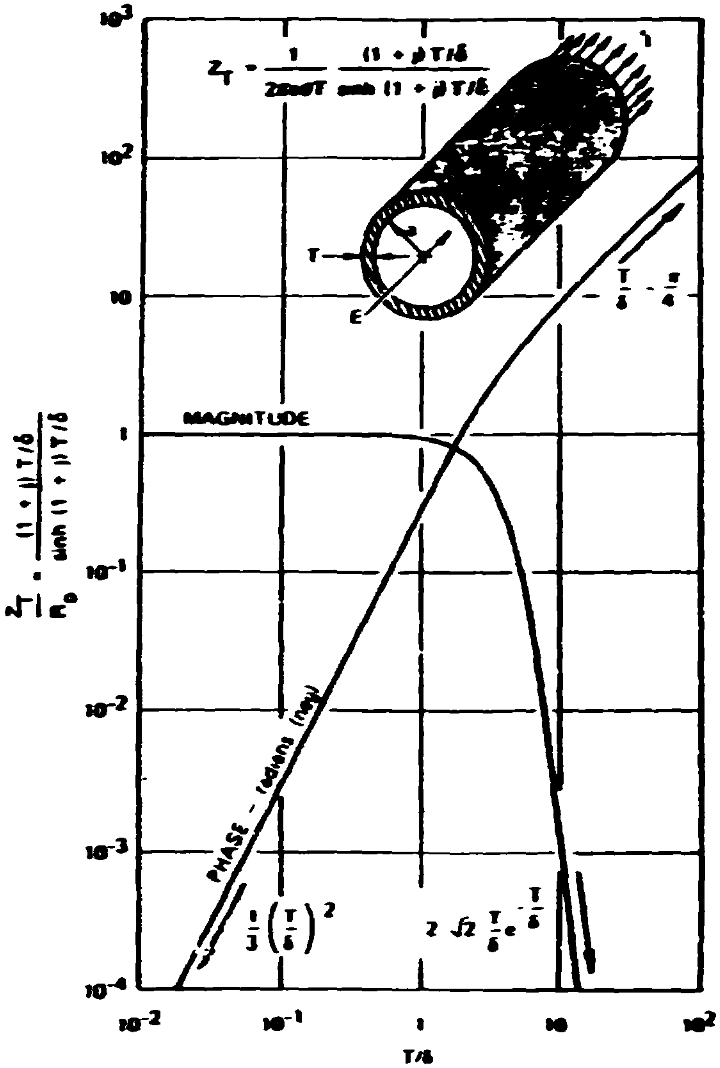
All other shields, such as braided-wire, tape-wound, flexible conduit, etc., are characterized by a leakage inductance that causes the coupling to the internal conductors to increase with frequency above about 1 MHz. Many of these shields also display the leakage capacitance mentioned above. Coupling through the leakage capacitance also increases with frequency.

The transfer impendance can be determined theoretically, especially for simple cable shields such as solid metallic conduit. For example, the transfer impedance of a thin-walled tubular shield is given by

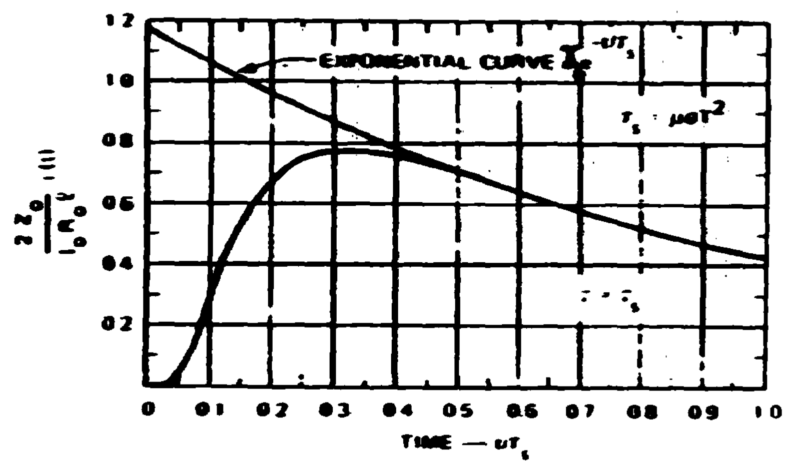
$$Z_T = \frac{1}{2\pi a \sigma T} \; \frac{(1+j)\, T/\delta}{\sinh\, (1+j)T/\delta}$$

where a is the radius of the shield, σ is its conductivity, T is the wall thickness, j is the unit imaginary number, and δ is the skin depth.

The transfer impedance given above is shown in Exhibit 4-16(a), normalized to the dc resistance per unit length R. The frequency dependance is contained in the skin depth on the abscissa normalized to the shield thickness. The low-pass filtering afforded by the shield is apparent when the thickness approaches the skin depth ($T/\delta = 1$). Exhibit 4-16(b) shows the resultant current waveform induced in the cable core, terminated in a characteristic impedance Z_C, for a sheath (shield) current represented by an exponential with a decay time constant (τ) approximately equal to the shield diffusion time constant ($\mu_o \sigma \tau$). This time response is valid for most shielding materials between 0.1 mm and 1 mm thick, for both aerial and buried cables, where decay times are approximately 1 μs and rise times are less than 300 ns.



(a) Normalized transfer impedance for solid tube



(b) Exponential response

EXHIBIT 4-16. Normalized Shield Transfer Impedance And Response To An Exponential Pulse.

Some geometries, however, such as braided coaxial cables, do not easily lend themselves to a theoretical treatment. For this reason, it is often preferable to experimentally determine the transfer impedance.

For braided coaxial cables, the transfer impedance is typically expressed in the form

$$Z_T = \frac{R_0\,(1+j)\,d/\delta}{\sinh\,(1+j)d/\delta} + j\omega\,M_{12}$$

where R_0 is the dc resistance per unit length, j is the unit imaginary number, d is the strand wire diameter, δ is the skin depth, ω is the angular frequency, and M_{12} is the leakage inductance per unit length.

A plot of the magnitude of the transfer impedance is shown in Exhibit 4-17 for various optical coverages (K). The parameters in the exhibit are given for some typical weave data (Ref. 5) for braided wire shields. The optical coverage tends to increase with the number of carriers (c) as would be expected. A K=100% would have a Z_T equal to that of a solid cylindrical tube (shown by the dotted curve). The dominance of the diffusion term well below 1 MHz and the dominance of the ωM_{12} term well above 1 MHz is apparent in Exhibit 4-17.

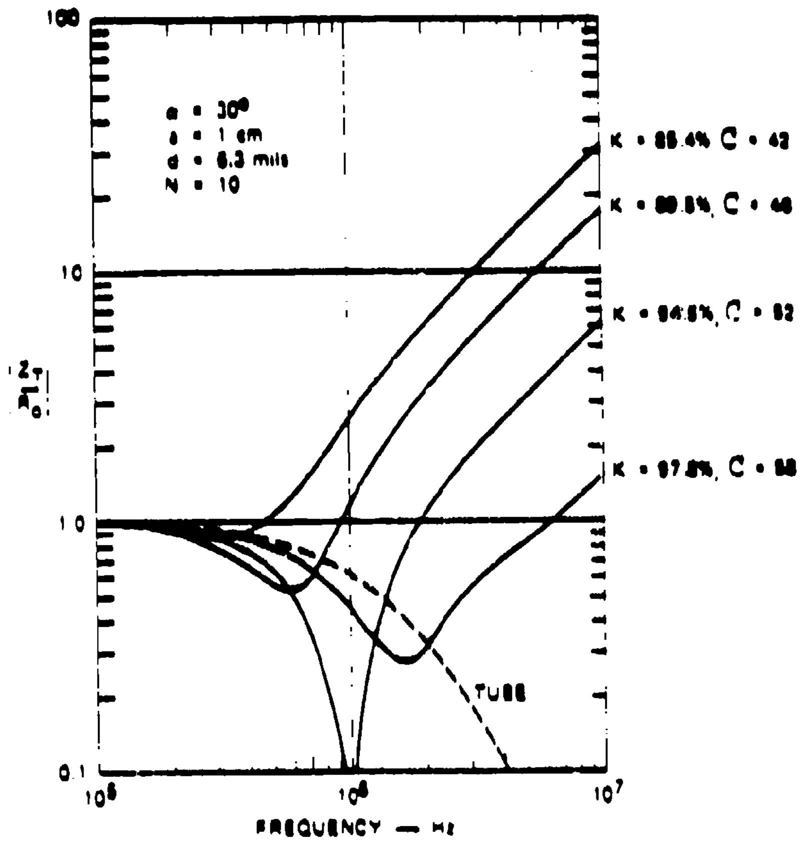


EXHIBIT 4-17. Transfer Impedance For Braided Wire Shields.

For typical braided coaxial cables, R_o ranges from 1 to 24 $m\Omega/m$ and M_{12} ranges from 0.1 to 1 nH/m. At low frequencies, $d/\delta \ll 1$ and $\omega M_{12} \ll R_o$ and Z_T reduces to R_o. For example, for an RG-58 coaxial cable at $\omega = 10^4$ Hz, $d/\delta = 0.24 < 1$ and $M_{12} = 0.01$ $m\Omega/m$. $R_o = 14.2$ $m\Omega/m$, so that the transfer impedance is approximately equal to R_o. A 500 A current on a cable length of 100 m will induce a voltage drop on the center conductor of (500 A)(100 m)(14.2 $m\Omega/m$) = 710 V.

Typical braided-wire shields used for interference control and for coaxial transmission lines have leakage inductances of the order of 0.1 to 1 nH/m, i.e., a 10 MHz-current of 1 A flowing through the shield will produce 6 to 60 mV of internal voltage per meter of cable. Single-layer tape-wound shields and flexible conduits formed of spiraled, interlocking turns may have much larger leakage inductance--often several μH/m. However, longitudinal tapes with overlapping seams and two-layer, counter-wound tapes are comparable to good braided-wire shields in terms of the leakage inductance.

Double layers of cable shielding can greatly improve the overall cable shield transfer function. The inner shield provides additional attenuation, and protects against fields generated by nonuniform current flow over the outer shield. One example configuration is a collection of 20 low-voltage signal wires with individual thin continuous shields, running together and enclosed within a braided shield. In this configuration, it is important to keep the two shield layers insulated from one another until they reference ground.

Much work has been done in studying the correct way to terminate cable shields; the dominant leakage through a shield may well occur at the connectors. Briefly, the best termination by far is a 360° low-impedance connector since it ensures closure and allows current to flow uniformly over the termination. In practice, pigtails are often used in lieu of connectors; this is not a good practice for EMP mitigation, as large induced currents may radiate strong fields that couple dangerous transients to even a few inches of exposed wire. If a pigtail is used, it should be short, never run parallel to the wire, and not pass through a surface into a shielded volume (see Exhibit 4-18).

4.4.4 Bonding, Grounding, And Treatment Of Building Penetrations

Since an entire central office can act as a large and efficient antenna for picking up HEMP, intentional and unintentional conductors can carry surge current to buildings that house protected equipment. Bonding and grounding can work hand-in-hand, or independently, to mitigate a transient entering a building, or piece of equipment.

Bonding means providing a low-impedance path along a conductor, or from one conductor to another; grounding means providing a path to reference ground (usually Earth ground). A low-impedance grounding path must be well bonded, but a well-bonded path need not be grounded.

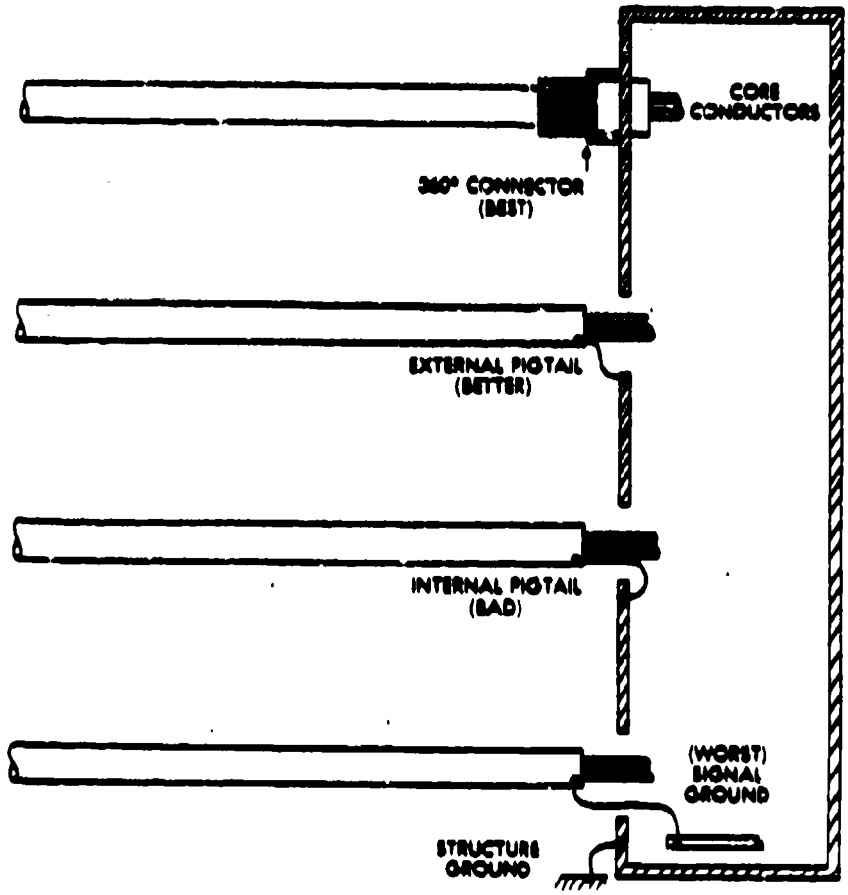


EXHIBIT 4-18. Shield Bonding And Grounding Techniques.

There are three basic aspects to consider when making a good bond. First, highly conductive materials are needed (this includes rivets and bolts, if used). Second, good joining techniques are important. In order of preference, these are: continuous welds, spot welds, solder or braze, pressure joints, rivets, and bolts (only if accessible for periodic tightening). Good common techniques include overlapping and bending back sheet joints and then welding specially designed RF gaskets, door jambs, etc., and brazed screens bonded to structure. Paint or nonconductive coating such as Mylar or Teflon must be removed to expose bare metal, and all joints must make continuous metal-to-metal contact. Peripheral bonds should be used for all pipe joints and terminations. Good technique can produce joints or straps with only milliohms of resistance.

The third aspect to remember is that low impedance means low inductance, which is especially important for HEMP transients where rise times are on the order of 10 ns. If bonding straps or jumpers are used, thev must be short and straight, and should never be longer than the space they are meant to cross.

Bonding and grounding paths protect both equipment and personnel. For example, imagine an average direct lightning stroke to a building penetration would have a peak current of about 2C kA and could cause extreme damage. EMP, by comparison, might couple 10,000 A onto each of a number of long conductors that enter the building. Damage protection includes conducting these currents to earth and reduction of the possibility of arcing and diversion of the surge currents. A plant engineer can satisfy both of these requirements by provision of a high-integrity conduction region to ground. For example, wide, thick connections should be chosen over narrow paths (which is another virtue of the 360° connector), and bonds need protection and inspection against degradation. Where large currents are expected, a high-integrity conduction region is needed.

Grounding techniques vary since grounding is often the responsibility of a construction or operations engineer at the site. At the building level there are two grounds: exterral for external cable shields, conductors, and commercial power; and internal for internal equipment ground. Neither of these should cross the building boundary. Even though the National Electric Code does not exclude the practice of passing green wire across the building boundary, there is never a reason to practice this method. A grounding wire from the outside that does come in might carry large currents and radiate high fields. An alternate approach, if the building has a bonded metal structure that is grounded, is to tie the exterior ground to the exterior of the structure, and the internal ground to the interior of the structure at a nearby point.

A grounding point in Earth is not an infinite current sink. Where large currents are anticipated, a good ground might be a large plate, or rods of varying lengths buried in a high conductivity ash. Metal structures of buildings in the PSN are often grounded at multiple points in a large, buried loop of wire. If good grounding techniques are not used, surge currents may reflect from the bad ground point (this is sometimes experienced in lightning strikes) and conduct to sensitive circuits upward via their ground. It is important to keep structure ground, and internal equipment and signal grounds separate.

Where conductors enter the building, the worst treatment would be random placing of penetrations not grounded at the building structure. Some currents may have a long way to go to find ground, destroying everything in their path. Better techniques are burying conductors where they approach the building, reflecting currents back away from the building, or bonding all conductors to one penetration plate that is connected to ground through a well-bonded path (see Exhibit 4-19 for an overview of penetration treatments).

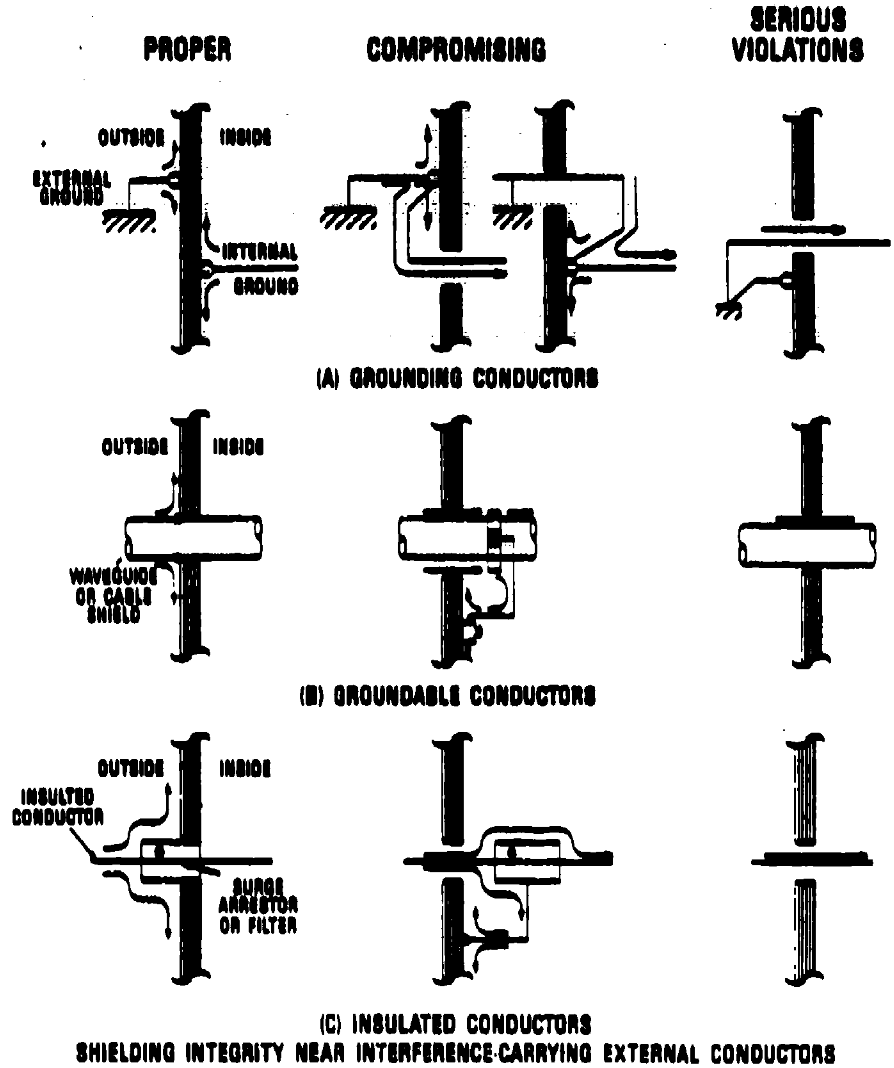


EXHIBIT 4-19. Treatment Of Penetrators.

The Defense Communications Agency (DCA) requires that all intentional conductors be buried for 100 feet before entering a building (Ref. 17), and that other conductors be bonded to site housing structures. Cables in the PSN are often buried as well; many lines follow weatherhead poles into the ground and enter the building from underground. This technique slows the rise time of the surge on the conductor, in addition to being a good safety measure.

Isolation is sometimes used to reflect lightning or surge currents back along a line. Where this includes using open circuits, it is probably a bad practice for EMP mitigation, as EMP-induced surges could easily arc over. Where isolation consists of inserting a length of nonconductive pipe into a conductive path, on the other hand, it is a very good practice as long as three conditions are met: the nonconductive length is long enough, a path to ground exists for the reflected current, and the pipe does not carry a conductive fluid (such as sewer or fuel).

The best treatment of conductive building penetrations is the penetration plate technique, where all conductors enter the building in one spot, and are bonded and grounded on the outside (see Exhibits 4-20 and 4-21, for the front and side views of such a plate). This technique is invariably used on military installations that require EMP protection.

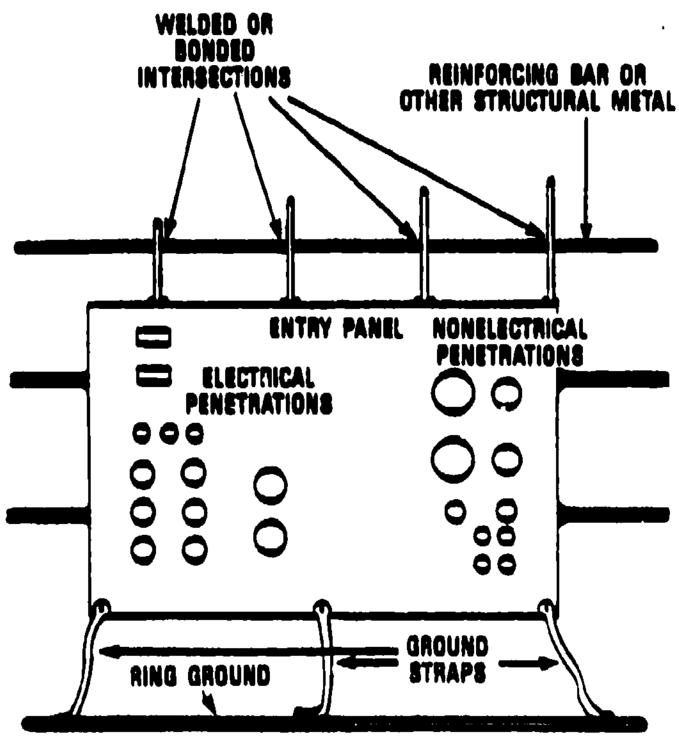


EXHIBIT 4-20. Penetration Plate, Front View.

4.4.5 Transient Protection And Filtering

As outlined in previous sections, conductors guide HEMP-induced transient currents to buildings. Therefore, power and signal lines

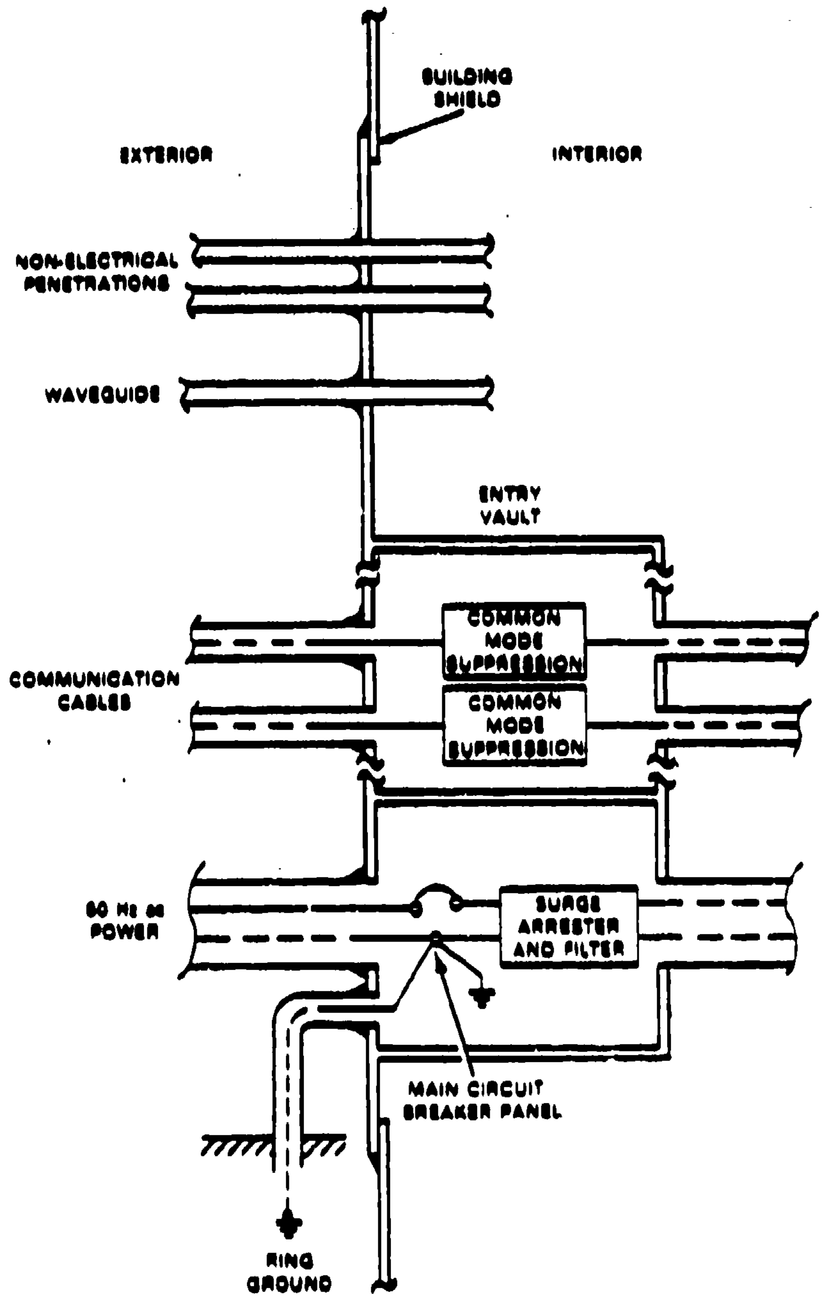


EXHIBIT 4-21. Penetration Plate, Side View.

that enter buildings need transient protection. However, even if diverted, surge currents on penetrating conductors radiate and conduct strong fields that couple to and inject on other conductors near the building walls. Thus, nearly all wires and interface circuits are exposed to transients. In this section, these EMP transients will be compared to power surge transients and lightning transients in terms of waveforms and energy content. Protection techniques, including surge limiting and filtering, are reviewed, followed by a discussion of hybrid protection circuits in the PSN.

Power surges are relatively common in the PSN. Most power surge protection techniques guard against system-generated transients, i.e., those produced by switching, breakdown, or intrasystem coupling from other lines. These are nearly always damped sinusoids lasting from 5 to 30 μs. Peak voltages of up to 5,600 V have been measured even though the dielectric strength of the cable is normally tested only to 1,000 V. Power surges have slow rise times, with highest frequency near 1.5 MHz; such low frequencies are relatively easy to protect against.

Lightning surges, which can be somewhat faster than power surges, are fairly common in the PSN as well. One lightning flash comprises thousands of small discharges and a few massive return strokes. The return strokes have been measured in some cases as having 1 μs rise times. Some recent data indicate that some strokes may have shorter rise times (Ref. 18). However, surges that inject onto long lines or towers and are observed at PSN buildings have rise times on the order of microseconds or longer. Continuing currents can last for a millisecond, but in practice can be clamped and damped in 30 μs like a power line transient.

EMP is expected to couple less energy to a single line than a worstcase lightning flash attachment, with about the same energy as a direct power line fault transient (Section 4.2 and Ref. 19). However, EMP surges are expected to rise more quickly. Therefore, the significant difference between a HEMP-induced pulse and other transients is the rate-of-rise.

Surge-limiting and filtering devices are major elements of an electrical protection scheme. In surge limitation, the principle is to provide a stand-by mechanism that appears as a high impedance to ground up to dynamic or static potential level, and allow current to pass to ground through a low impedance.

The following discussion concerns nonlinear surge protection devices and their effects on surge waveforms, filtering devices and their effects on waveforms, and combinations of protection used in the PSN.

Assuming that surge limiting devices have been installed properly, two major considerations apply to their application: they have a finite response time to any input transient and the "clamping" action generates high-frequency switching noise that can pass into the equipment. These features are not uniquely specified for each device, but depend on the rate of rise of the incoming pulse (volts/sec), manufacture (technology), method of installation, and lead inductance.

Several types of nonlinear devices exist. Names commonly used to refer to these devices are voltage dividers, surge-limiting devices, surge arrestors, or Terminal Protection Devices (TPDs). The operation of these limiters can be through switching or nonswitching mechanisms. Switching refers to the change in conduction state (reducing voltage or current to a low level) after achieving a specified voltage level. Examples of switching devices are spark gaps, thyristors, fuses, and circuit breakers.

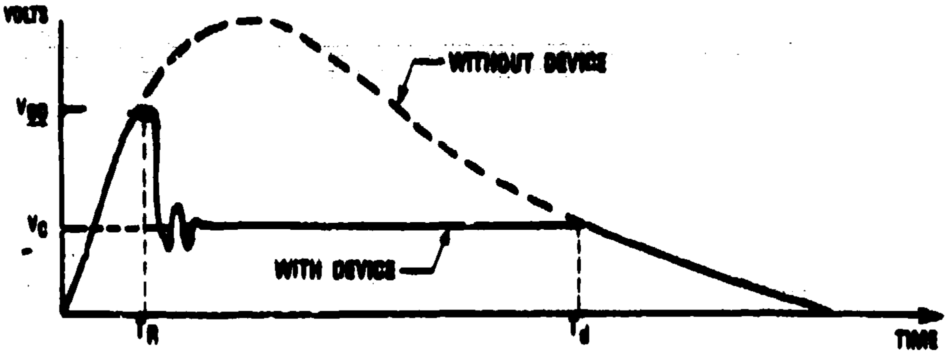
Nonswitching devices (e.g., varistors, Zener diodes) also shunt but do not undergo a change of state. Here the voltage and current are related in a nonlinear fashion such as represented in the equation below, where I is the current, V is the voltage, and k,α are parameters that are device dependent. This V-I relationship exists when the voltage exceeds the breakover voltage for varistors, or forward threshold and reverse breakdown voltages for diodes. In general, the larger the α, the better the clamping.

$$I = kV^{\alpha}$$

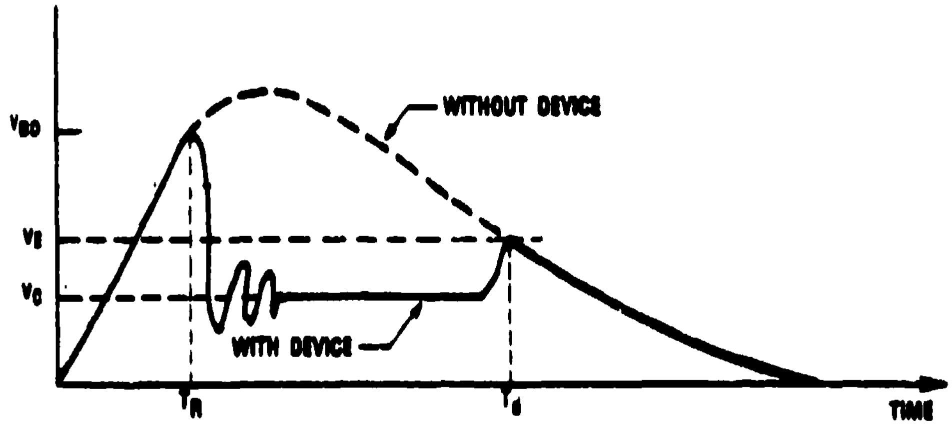
Exhibit 4-22 illustrates the effect that surge arrestors have on transients in the time domain. Exhibit 4-22(b) shows the effects of a carbon-block spark-gap device, widely used in the PSN. The altered wave shape due to clamping is affected by several parameters. Probably the key parameter is the response time of the device, which determines the pulse breakdown voltage (V_{BD}) (the voltage at which clamping begins). The response time is a function of the intrinsic mechanism of the device as well as the inductance associated with its installation. For switching devices, the finite time to change conduction state may take 100 ns or longer. For nonswitching devices the response may occur in less than a nanosecond. Exhibits 4-23(a), (b) show the effects of rate-of-rise on firing time, and show some typical firing time data.

The time domain effects in Exhibit 4-22 can be described, for purposes of illustration, by a damped sinusoid plus a square pulse that begins at time T_R and ends at T_d. In actuality, the ringing associated with the fast clamping action may be composed of many damped sinusoids with different frequencies.

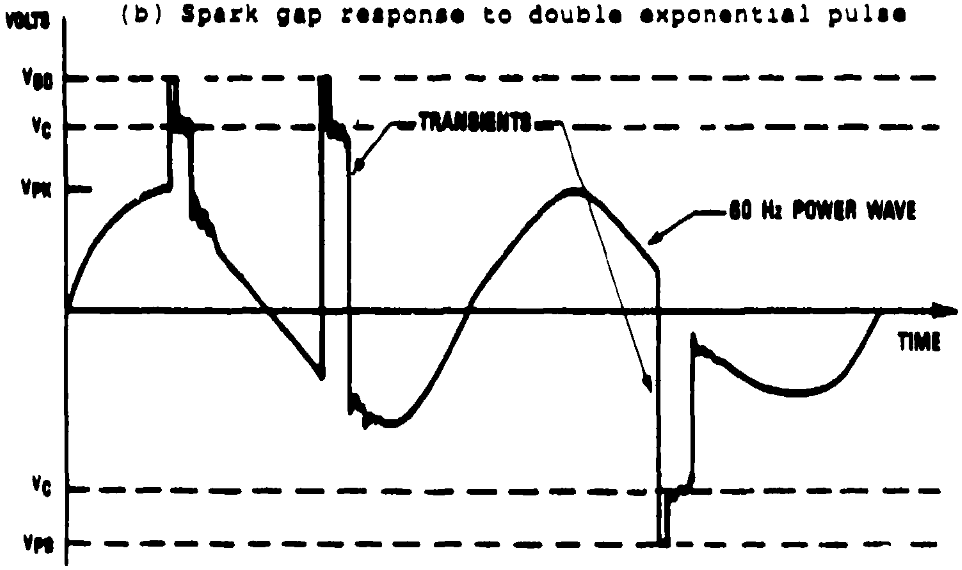
The difference between the pulse breakdown voltage (V_{BD}) and the clamping voltage (V_C) is also called the overshoot voltage, and is a function of the rate-of-rise of the input signal and the response time. The maximum normal voltage (V_{mn}) is the voltage at which the arrestor begins to conduct for a very slow rate-of-rise (dc). The clamping voltage (V_C) is the voltage that appears across the protector terminals after the overshoot has decayed, and is dependent on the current through the device. Finally, the extinguishing voltage (V_E) is a dc voltage that allows the protector to self-quench, or extinguish, after surge firing.



(a) Varistor or Zener response to double exponential pulse

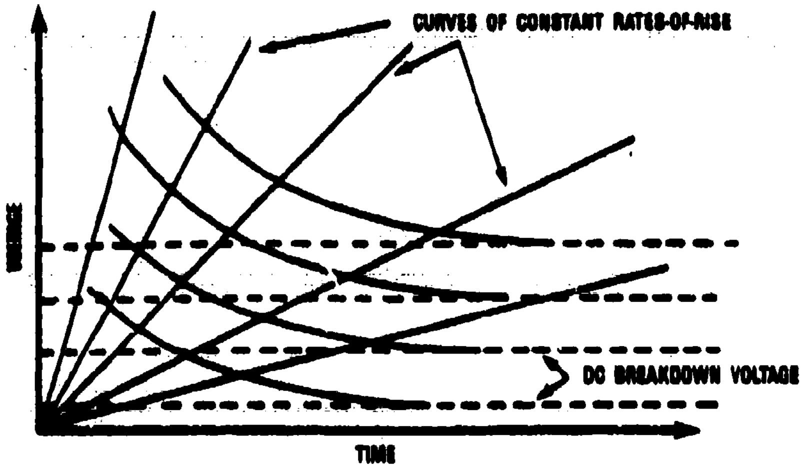


(b) Spark gap response to double exponential pulse

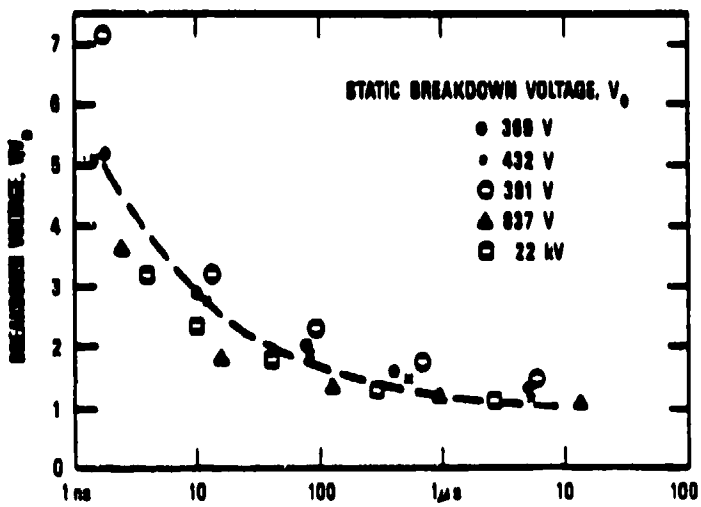


(c) Powerline application of spark gap

EXHIBIT 4-22. Time Domain Response Of Nonlinear Devices To Transients.



(a) TYPICAL INCREASE IN BREAKDOWN VOLTAGE OF A GAP VS. RATE OF RISE OF TRANSIENT



(b) TYPICAL DATA

EXHIBIT 4-23. Firing Characteristics Of Carbon Block Surge Arrestors.

The transition time from V_{BD} to V_C can be from 1 to 5 ns. As mentioned previously, this fast switching time results in high frequency, broadband noise. A convenient representation of the waveform in Exhibit 4-22 can be described by a damped sinusoid (amplitude V_{BD}) that damps in 3 ns, and a square pulse of width $(T_d - T_R)$ ns with amplitude V_C.

$$V(t) = V_{BD}\, e^{-\alpha t} \sin\beta t + V_C\, [u_{Td}(t) - u_{Tr}(t)]$$

$$V_{BD} > V_C,\ \alpha = 3.33 \times 10^8\ \text{SEC}^{-1}$$

$$T_d >> T_r,\ \beta = 8.33 \times 10^9\ \text{SEC}^{-1}$$

The accompanying frequency spectrum is shown in Exhibit 4-24 labeled "with limiter" described by the Fourier inversion of V(t).

$$|V(\omega)| = V_{BD}\, \beta \Big/ \sqrt{(\beta^2 + \alpha^2 - \omega^2) \quad + 4\,\alpha^2\omega^2}$$
$$+ \frac{2V_c}{\omega} \sin\left[\tfrac{1}{2}(T_d - T_r)\omega\right] \cos\left[\tfrac{1}{2}(T_d - T_r)\omega\right]$$

Exhibit 4-24 illustrates the effect that the limiter has on a 1 V double exponential input. It is assumed that the limiter fires at 1 V so that all the curves are normalized to 1 V. The clamping action generates noise in the gigahertz region of the spectrum, yet the overall energy in the input signal is shunted. Combining a low pass filter with a limiter mitigates this adverse noise generation. Further discussion of the aspects of hybrid combinations is presented following the discussion of filters.

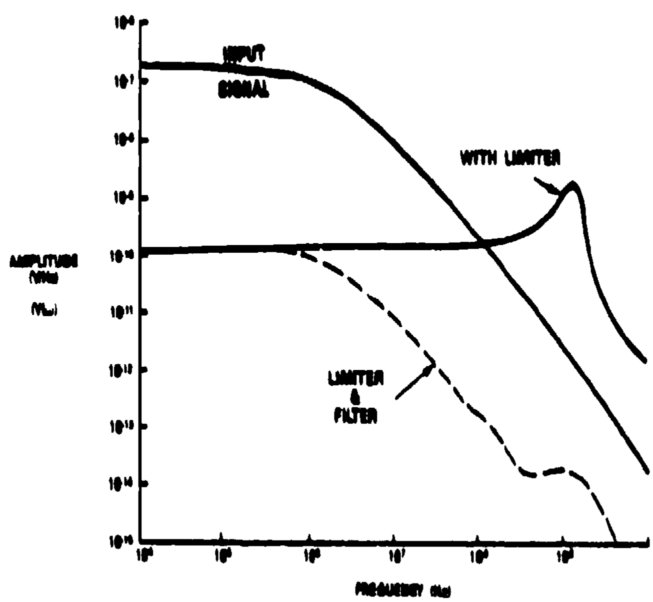


EXHIBIT 4-24. Effect Of Limiters On HEMP-Induced Waveform In The Frequency Domain.

Nearly all filters are on equipment interface circuits. However, some filtering could occur at boundary 1. The batteries on power lines act as large shunt capacitors to ground, which is very efficient at absorbing transients that make it through the transformer and spark gaps. Also, long lines (especially buried lines) act as inductors, slowing down rise times of the induced surges.

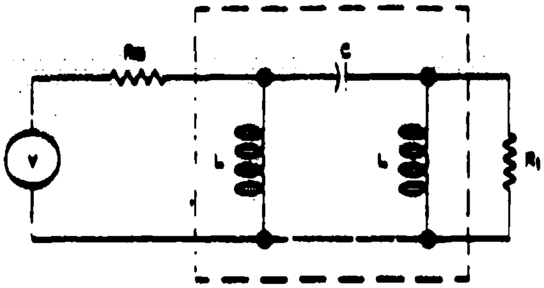
The attenuation characteristics of filters can be measured in accordance with the insertion loss requirements of MIL-STD-220A. These tests require that the source and load impedances be matched at 50 ohms. For the most part, these load conditions cannot be met at all the frequencies in the threat spectrum and under all the loads expected in an operational facility. The filters shown in Exhibit 4-25(a), (b) are known as pi-section filters. Three element filters (e.g., C, L, C), such as the pi-section, are tolerent of impedance mismatches; multisection filters (e.g., Butterworth filters) are even more tolerant, but tend to be more expensive.

The bandpass filter design of Exhibit 4-25(c) is indicative of a filter applied to commercial (10 kHz) communication lines or antenna inputs. The bandpass is designed to receive signals in the operating frequency of the antenna (which may also receive significant energy from the EMP spectrum). In this case, the filter has multiple sections with lightning and EMP protection afforded by the ESA and Z1 element of the filter.

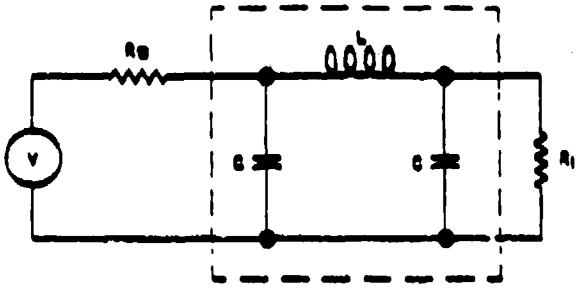
The frequency attenuation characteristics of the various filters discussed above are shown in Exhibit 4-25(d). Multisection filters have a steeper rolloff in the freqency domain than two element filters (e.g., RC, LC filters have a 20 dB/decade rolloff beyond the cutoff frequency).

The damped sine waveform described in Exhibit 4-14 has a Fourier transform (frequency spectrum) represented by Exhibit 4-26(a) labeled "without filter." The spectrum labeled "with filter" is the effect a low-pass pi-section filter (depicted in Exhibit 4-25(b)) has after attenuating the damped sinusoid. The attenuation of high-frequency components results in the reduction of the rate of rise of a transient. As discussed in Section 4.2, any transient coupling from free space to cables or cable sheaths into interior wiring has an inherent low-pass filtering (transfer impedance) due to inductive reactance and ac resistance (skin effect).

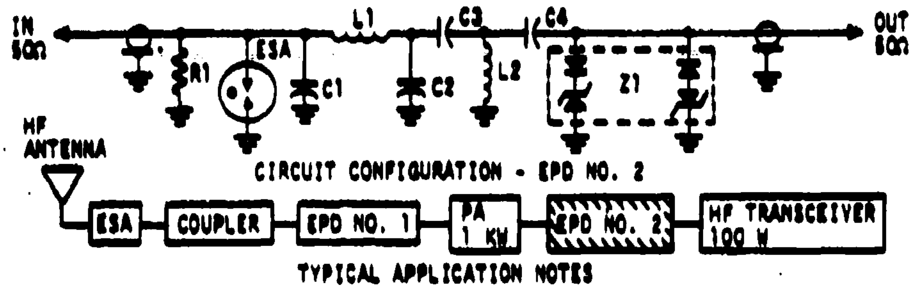
The time domain waveforms shown in Exhibit 4-26(b) show the effect a low-pass filter has as a function of cutoff frequency. The unfiltered pulse with a 25 ns to 30 ns rise time, is nearly unaffected by the 100-MHz cutoff filter since most EMP energy is below 100 MHz where attenuation begins. In comparison, filters that have a rolloff above the voice frequencies (3 to 5 kHz) and twisted pair frequency transmission range increase the time-to-peak of the transient by an order of magnitude and decrease the amplitude by a factor of 15 dB.



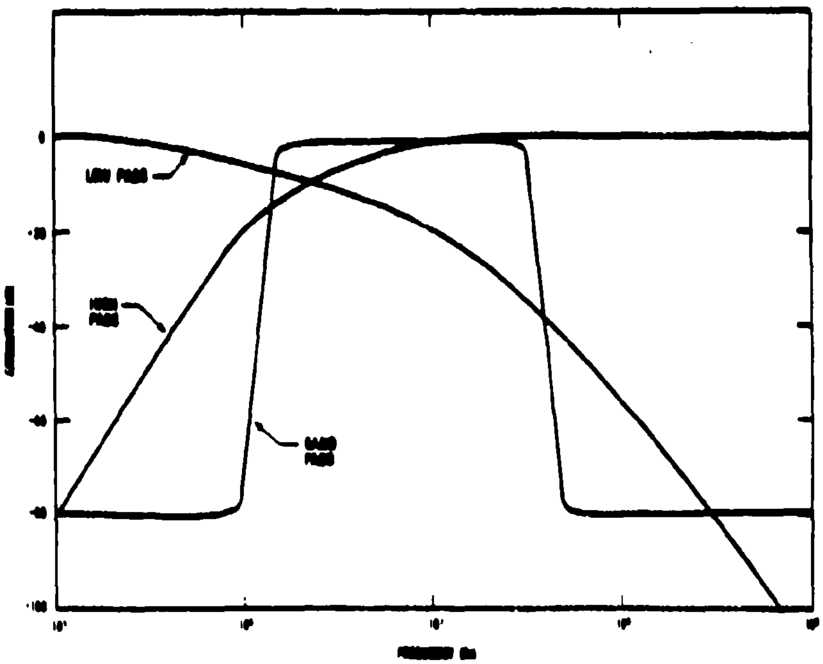
(a) High pass filter



(b) Low pass filter



(c) Band pass filter - HF transceiver for EMP protection



(d) Filter Attenuation Characteristics

EXHIBIT 4-25. LRC Filter Characteristics.

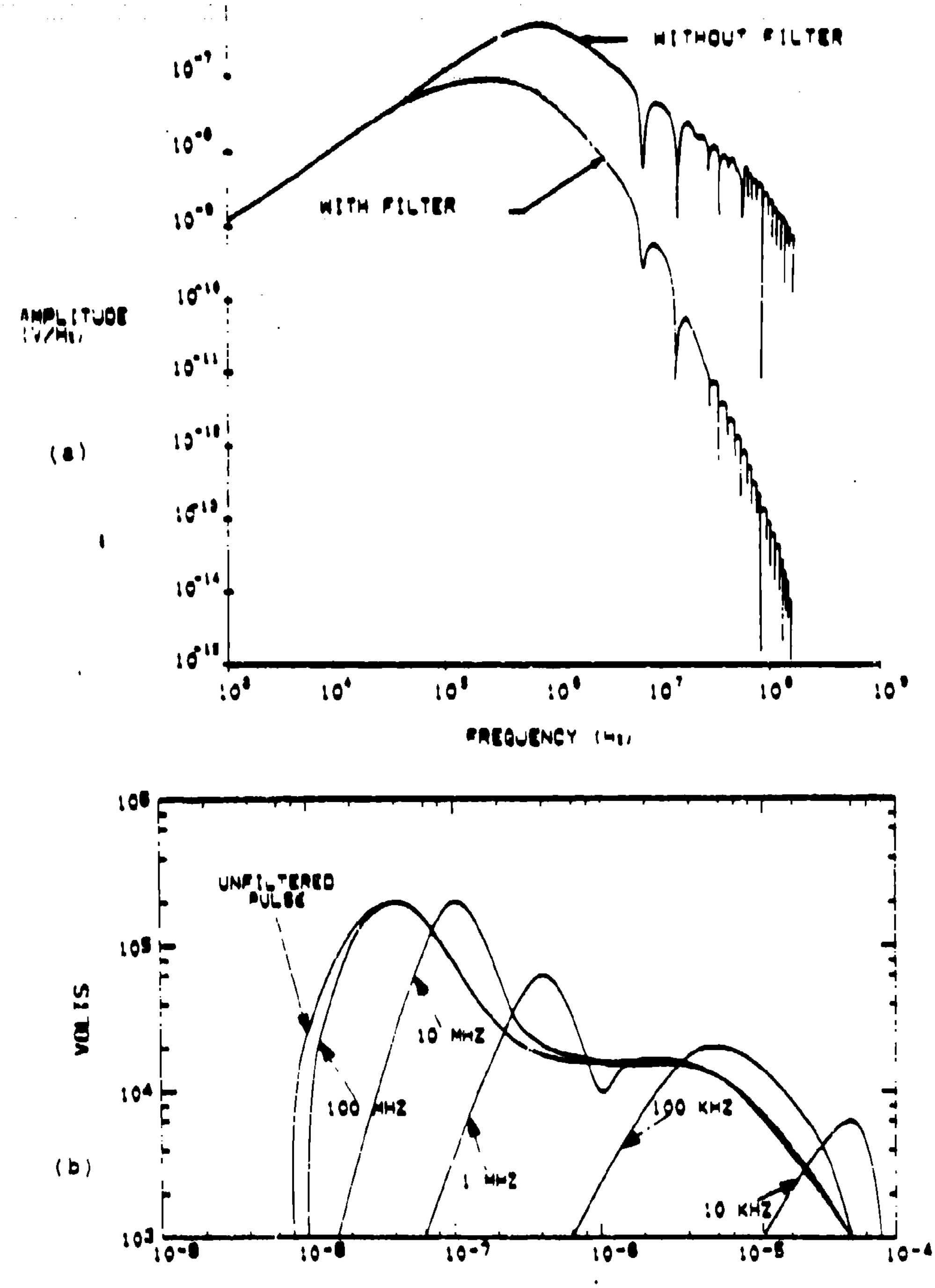


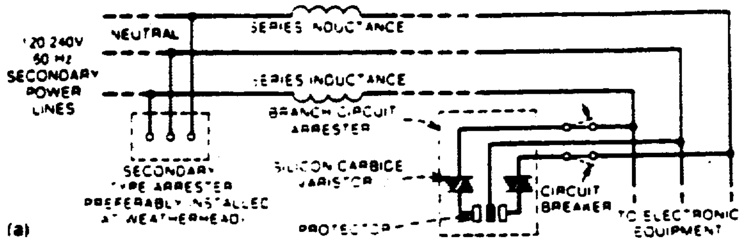
EXHIBIT 4-26. Low-Pass Filter Effects In The Time And Frequency Domains.

Of all protection schemes, the most common and most reliable are hybrid circuits (combinations of more than one protection element) that can cancel the adverse effects of individual devices. As common practice at some telephone plants, hybrid circuits are made up of carbon block spark gaps and circuit breakers on power lines, and carbon blocks with semiconductor clamping devices on signal lines (see Exhibit 4-27). In addition, a generic PSN power supply line has a transformer, another spark-gap, a rectifier that can normally carry on the order of 100 A, and large capacity batteries tied to ground.

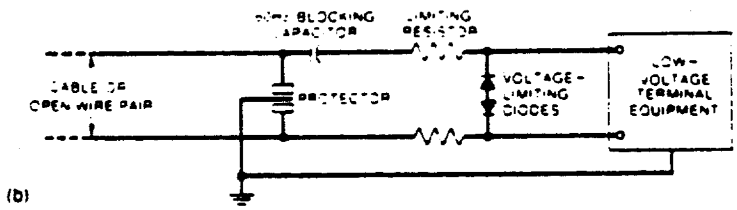
4.5 SUMMARY OF STRESS LEVELS

Exhibit 4-28 presents typical HEMP-induced transient levels, as developed by analysis or observed in site tests. The transient levels are representative of worst-case values at boundary 1. The table also shows that some of the current transients preserve a double exponential time waveform, whereas in other cases, a more narrowly tuned response results (damped sine).

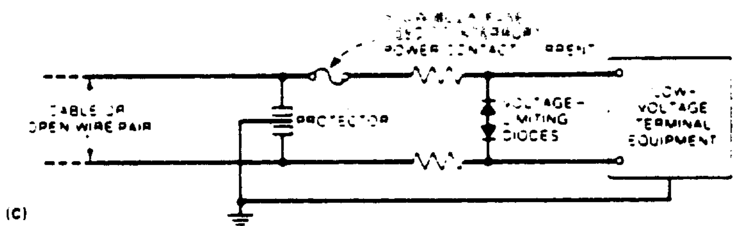
The listed current value for direct illumination is the observed 95 percentile value for interbay cables in buildings designed with no intentional shielding. This corresponds to current induced by zone 1 diffused fields on internal cables at boundary 2 interfaces. The values for the other penetrations are representative of the signal strengths external to the building. The internal signal strengths may be reduced depending on the bonding, grounding, protection devices, and distribution of the interbay wiring throughout the interior of the building with respect to the points of entry.



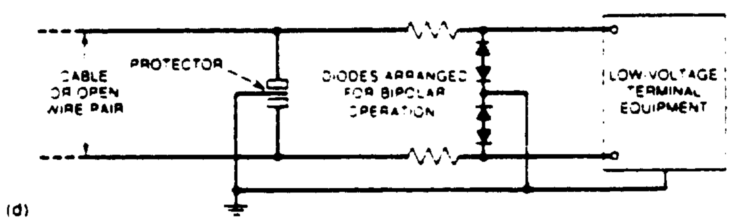
(a) Low-voltage branch power circuit



(b) Carrier equipment



(c) Voice-frequency equipment



(d) Diodes at equipment terminals

EXHIBIT 4-27. Representative Lightning Protection Circuits On Telephone Plant Equipment.

PENETRATION	THREAT WAVEFORM	EMP INDUCED CURRENT
Long lines:		
Aerial	D.E.	4 kA
Buried	D.E.	2 kA
Microwave Tower/ Waveguide	D.S.	6 kA
Short Local Conductors (utilities)	D.E.	1 kA
Direct Illumination	D.S.	20 A

Key: D.E. = Double Exponential
D.S. = Damped Sinusoid

EXHIBIT 4-28. Summary Table Of Stress Values.

5.0 TRANSMISSION FACILITIES

5.0 TRANSMISSION FACILITIES

This chapter presents the EMP responses of critical transmission facilities identified in Chapter 3. These facilities include the T1 digital carrier, the FT3C optical fiber system, the L4/L5 coaxial cable, and the TD-2 microwave radio systems. Some background on function and hardware is presented for each system, followed by a discussion of coupling to outside plant equipment, stresses conducted to line repeaters and central office equipment*, and exposure of all equipment to direct illumination fields. Relevant tests and analyses are outlined, and the responses of system elements and overall transmission systems to the 50 kV/m double exponential HEMP threat are discussed.

5.1 T1 CARRIER SYSTEM**

The T1 System was introduced in the early 1960s as a digital carrier of short-haul interoffice traffic. It transmits, over two pairs of wires, 24 two-way voice channels multiplexed as pulse-code-modulated (PCM) 1.544 Mbits/s signals. The system has evolved to include subscriber loop and customer premises applications.

A T1 carrier system comprises cable, line repeaters for signal amplification, and central office equipment including main repeaters, protection switching equipment, and channel banks. Maintenance, trouble isolation, and automatic switching are organized on a span basis. An average system is made up of four span lines and is 15 miles long; recent advances in engineering allow systems of up to 150 miles in length.

Line repeater fault-locate filters are designed to allow problem isolation from tests conducted in a central office. Additionally, protection switching equipment is used to automatically reroute multiplexed bit streams from failed pairs to spare pairs carried in each cable.

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* In this chapter, the term central office (CO, Office, Terminal Office) represents a repeated transmission segment end station, which is a PSN building that may be staffed.

** Significant portions of this section are drawn from the 1984 six-volume T1 EMP/MHD Hardness Assessment/Design by AT&T Bell Laboratories (the T1 Carrier Study). This study was undertaken to compare the EMP survivability of a particular lightning-protected route near Omaha, Nebraska, with that of a specially designed EMP-protected version of the same route. Only the lightning-protected system is considered in this report.

A typical T1 carrier system might be arranged as shown in Exhibit 5-1. At an intermediate CO (e.g., in the lower box) the entire digroup is demultiplexed. This is done so that some voice-frequency (VF) channels may be directed to a customer while the remaining voice-frequency channels are multiplexed onto the outgoing T1 carrier. The third type of office configuration shown in Exhibit 5-1 (upper right) is used only for supplying power to the T1 carrier line.

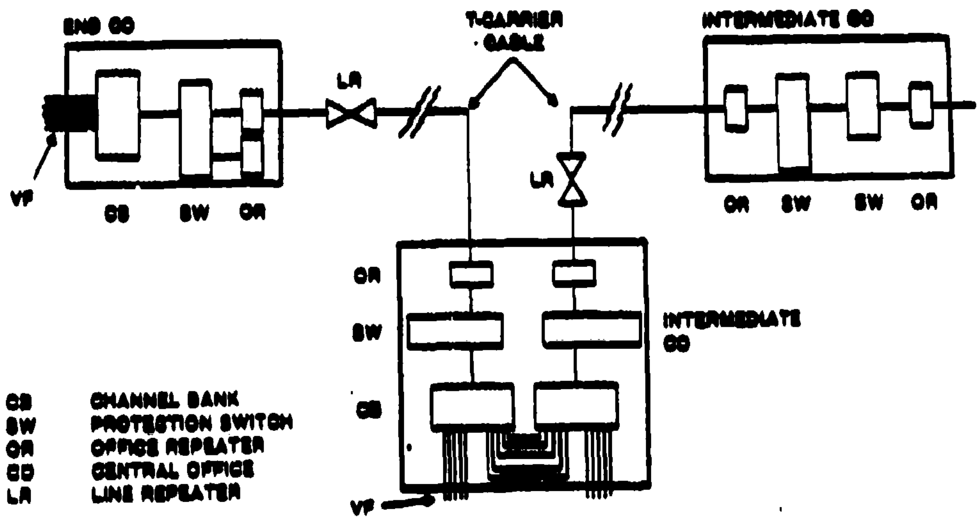
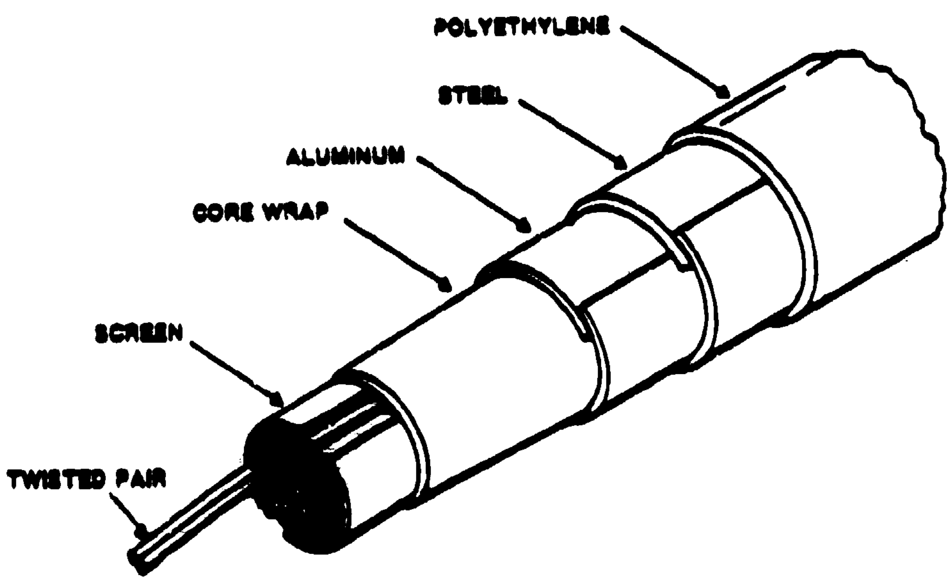


EXHIBIT 5-1. Typical T1 Carrier System Configuration.

5.1.1 EMP Effects On The Cable

T1 carrier was originally designed to be used only on twisted pair, voice-frequency transmission cables. Today, other types of cables are used for T1 carrier, some specially designed for T1 carrier use. Two such cables are the shielded 54- and 158-pair lines, shown in Exhibit 5-2. However, expanding the channel capacity of existing voice-frequency cables is still a major application of T1 carrier systems.

A number of potential problems can arise from EMP energy induced onto long lines by direct illumination. First, induced sheath currents on one-mile segments between repeaters produce very high sheath currents at COs and at repeaters. Such surges might cause direct damage to trunks or to equipment when seeking ground. Additionally, sheath currents diffuse to internal twisted pair conductors and induce surges on those signal leads. Currents induced on the leads might cause damage to repeaters or to terminal equipment either as fast high-voltage transients or as low-frequency high-voltage surges. These transients on signal leads would be the more serious threat (apart from direct damage to cables) if good bonding practices were not in use. If good



Transmission media: pulp, air-core PIC, or jelly-filled
PIC cables from 16 to 26 AWG. (Ref. 20.)

Sheath radius:

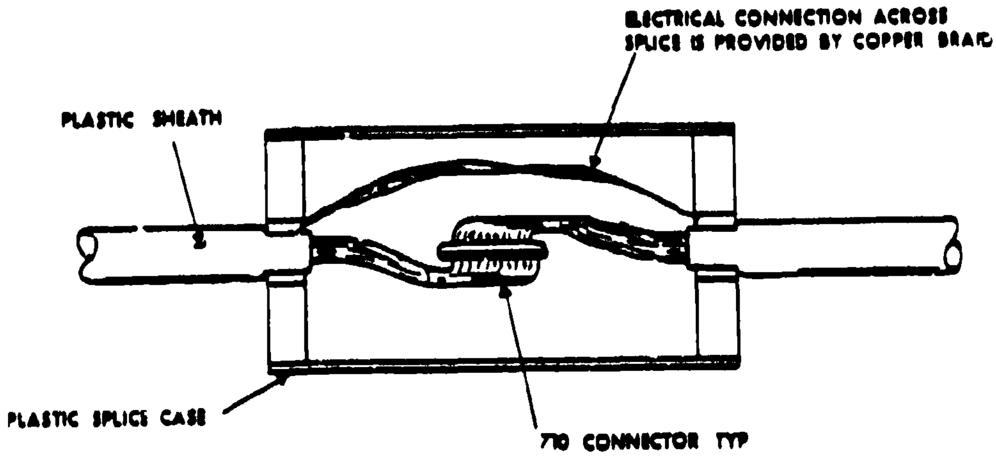
158-pair cable	r = 0.017 m
54-pair cable	r = 0.011 m (Ref. 21.)

EXHIBIT 5-2. T1 Carrier Twisted Pair Screened Cable.

bonding practices are not used, and signal leads are openly exposed to induced sheath currents, a major problem would be the direct coupling of transients to signal leads creating a serious threat to repeater and terminal equipment.

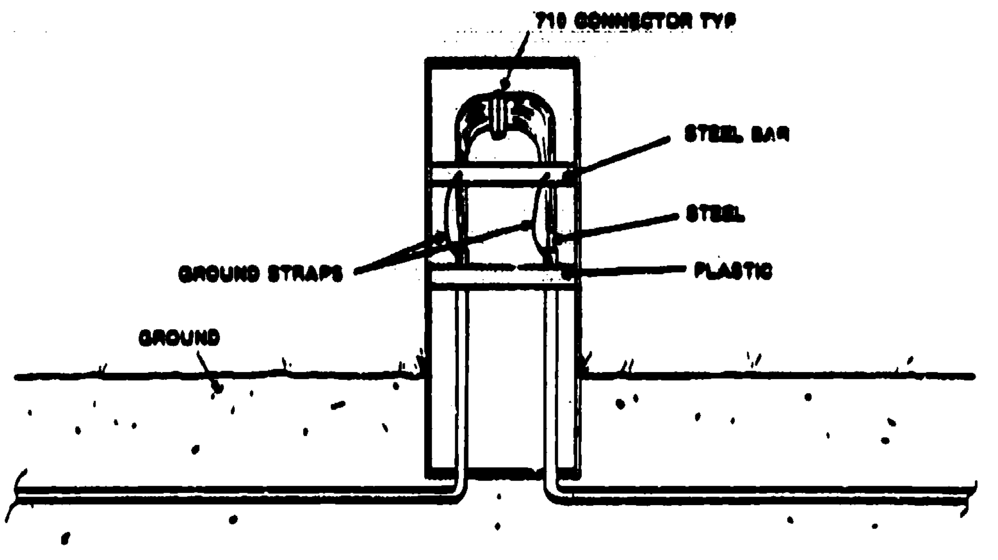
In a typical T1 cable in the field, good practices from an EMP perspective for continuously bonding the cable sheath are not always used. The major violation occurs at cable splice points. In a typical plastic splice case, a copper braid makes a dc sheath-to-sheath connection for safety purposes, running alongside unshielded signal leads. Even when a steel splice case is used, a bonding jumper is carried inside the case. Three types of typical splice cases are shown in Exhibit 5-3(a), (b), and (c). Such splices are not designed to carry surge currents. Pigtails (bonding straps) are not usually well-bonded to sheaths, do not provide enough surface for conduction of high surges, and easily degrade over a period of years.

A theoretical prediction of currents induced on a long cable sheath with splice cases inserted has never been done. A continuous long sheath is used for predictions, and values from such an analysis are presented in Chapter 4 for ideal aerial and buried cables. Actual long lines cannot be illuminated experimentally, but it is reasonable to assume that actual amplitudes would not be higher, and actual rise times would not be faster, than those calculated for ideal sheaths. However, a few splice cases that allow enhanced coupling to signal leads could cause significantly higher EMP transients at terminal equipment.

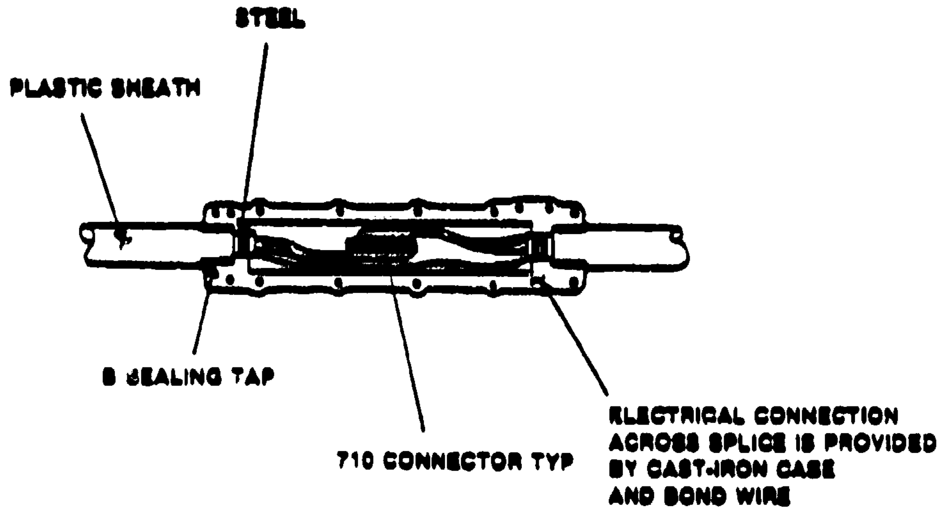


(a) Plastic Splice Case

EXHIBIT 5-3. T1 Carrier Splice Cases.



(b) Cast Iron Splice Case



(c) PC-12 Splice Case

EXHIBIT 5-3. (continued) T1 Carrier Splice Cases.

Accepted values for HEMP-induced sheath currents are on the order of 2 kA with rise times of 200 ns in buried cable, and on the order of 10 kA with rise times of 20 to 2000 ns in aerial cable, depending on the polarization, angle of incidence, and azimuth of the incident field. The measured values presented in the T1 Carrier Study are consistent with these expected values.

In one test listed in the T1 Carrier Study, a 1,200-foot 158-pair cable was exposed to the Repetitive EMP Simulator (REPS) at Harry Diamond Labs (HDL) in a simulation of double exponential pulse plane-wave illumination.

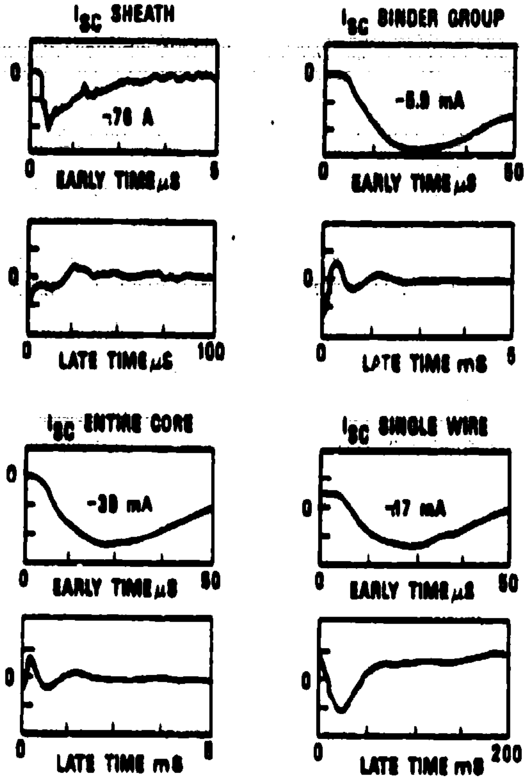
Induced currents measured on different parts of the cable are shown graphically in Exhibit 5-4. For 760 mA measured on the sheath, 39 mA was measured on the entire core (158 wire pairs). Assuming the relation between the two levels is linear, determined by the transfer impedance, and extrapolating to the worst-case theoretical induced current levels for the full threat (2 kA on buried cable and 4 kA on aerial cable), about 100 A and 200 A respectively could be induced on the core. The test report goes further to equate this to about 0.5 A on each signal lead, and adjusting for the worst case, concludes that not more than 2 A common-mode would be induced on any signal lead for buried cable. Aerial cable would have currents higher by a factor of 2. For a 100 Ω source impedance on buried and aerial signal leads, this corresponds to 50 V and 100 V open-circuit voltage respectively (for 0.5 A and 1 A), or for the worst-case, 200 V and 400 V (for 2 A and 4 A).

Rise times were measured as 500 ns on the sheath and 20 μs on a single wire, with double-exponential shaped pulse durations of 50 to 100 μs. These are within the range of accepted values, and are not expected to change for the full 50 kV double-exponential pulse threat.

Note that on the test setup, the signal leads were shielded for their entire length; this is not a good assumption for typical T1 systems, as leads break out and are exposed to a copper braid (that may be carrying 4 kA) in splice cases. Therefore, although currents and voltages calculated above give a good quantitative description of diffusion currents, they may not be the most important coupling contributions in typical systems; actual levels may be significantly higher.

5.1.2 EMP Effects On Repeaters

Regenerative repeaters on the central office and on the line retime and regenerate transmitted bipolar signals. Repeaters are solid-state plug-in units suitable for pole mounting or manhole placement. The transmitted digital signal travels on twisted pairs, balanced to ground, which have a nominal source impedance of 100 ohms. Spacing of



SHEATH→CORE→BINDER GROUP→WIRE

760 mA→39 mA→5.9 mA→.17 mA

SHEATH/CORE ~ 20/1

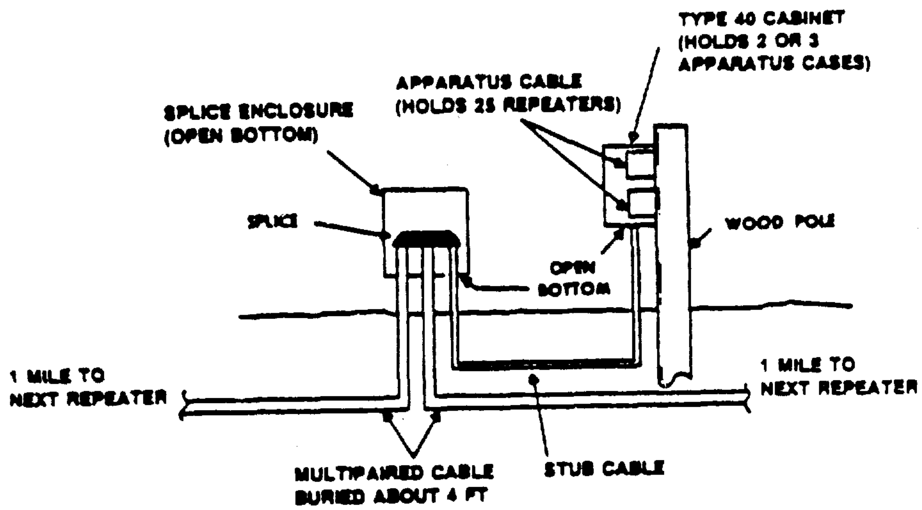
CORE/BINDER GROUP ~ 7/1

BINDER GROUP/WIRE ~ 35/1

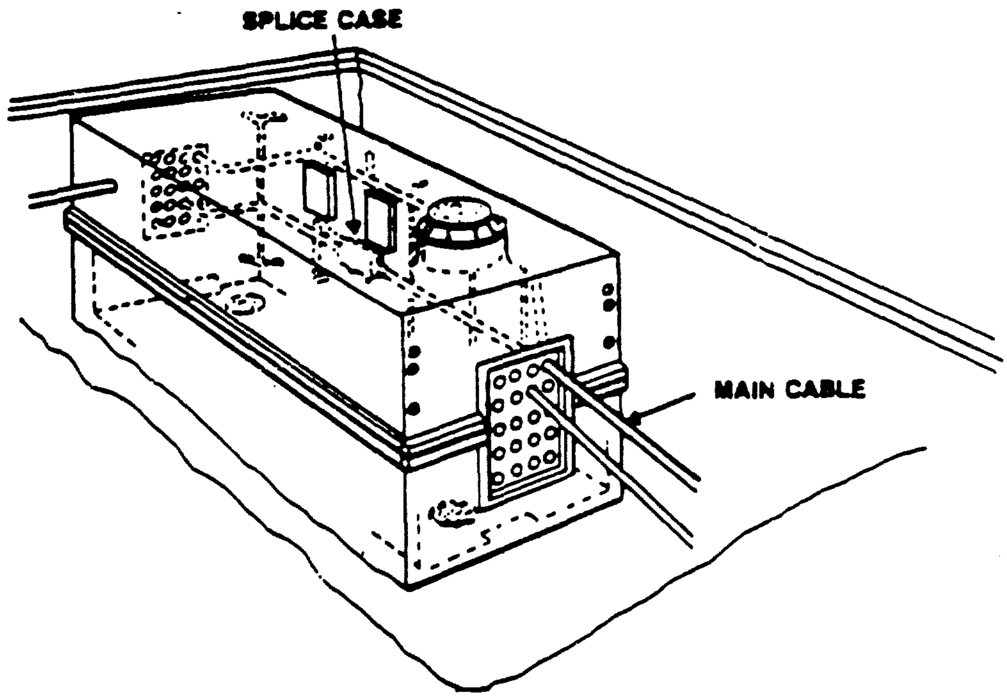
EXHIBIT 5-4. EMP-Induced Currents On T1 Cables.

T1 repeaters ranges from one mile to 6,000 feet. Typical pole-mounted and manhole repeater installations are shown in Exhibit 5-5(a) and (b). The dc power for repeater equipment is supplied over the digital transmission line. Line repeaters are powered in a series loop containing up to 17 repeaters.

The repeater cases installed on T1 carrier systems are the 818-/819- type. These are designed to house 25 T1 carrier repeaters, a fault-locate filter, a pressure contactor, and other apparatus. These repeater cases are molded from a fiberglass reinforced plastic. Numerous types of splice cases are in use in T1 systems. Typically, each



(a). Pole-Mounted Repeater



(b). Manhole-Installed Repeater

EXHIBIT 5-5. Typical T1 Repeater Installations.

has a copper braid bridging the gap from sheath to sheath where signal lines break out to the splice connector.

From an EMP perspective, T1 repeaters can be grouped according to their hardness against transients. There are unprotected repeaters, lightning protected repeaters, and 60 Hz hardened repeaters (on lines where power line fault transients can be expected). Technologies vary, and a myriad of repeater types are used; they may contain discrete components, standard or low-power ICs. More robust components are used for protected repeaters, and gas tube protection devices may be installed in the equipment case outside the repeaters.

Since T1 signals are digital, and repeaters detect and regenerate rather than amplify them, neither high- nor low-frequency pulse components on signal leads will be amplified and passed along the cable. Therefore, the major concern in repeater susceptibility is whether the circuits will survive when exposed to transients coupled onto signal leads over the one-mile interrepeater lengths.

Lightning-protected repeaters are designed and tested to withstand 600 V, 10 μs x 1,000 μs (rise time, fall time) double exponential pulses. Diffusion currents (Section 5.1.1) from a 50 kV double exponential pulse should produce only a 200 V 20 μs x 40 μs pulse at the repeaters, well within the lightning waveform.

The T1 Carrier Study describes two series of tests that addressed repeater susceptibility to the effects of these transients: EMP field-tests and current-injection tests. The first test, at HDL, used the Army EMP Simulator Operation (AESOP) and Office Sinusoidal Simulator (OSSI) combination to pulse fields onto a 2,000-foot T1 trunk with a splice case and pole-mounted repeater at its center. In this test, high-level fields and induced lead currents were simultaneously directed onto the repeater. Tests were done on a lightningprotected repeater and a special EMP-hardened repeater; only the lightning-protected repeater tests are discussed here.

The typical repeater unit tested was an 800-type plastic case housing two 239 E/F 60 Hz protected repeaters with standard lightning protection devices, 208A gas tubes, installed. The splice case was a typical PC-12 mounted above ground. During testing, outages in equipment operation of 2 μs to 256 ms were experienced, but no failures were seen.

In addition to subjecting equipment to high-level fields, the tests at HDL provide experimental justification for prediction of coupling of energy from sheaths and sheath termination straps to exposed signal leads. Extrapolation of test observations to worst-case levels indicates three components of induced current depending on the time domain. The first is high-frequency ringing or a double exponential surge, depending on the sheath length, and is quickly damped (in about a microsecond). This high frequency signal is due to the equipment response of the incident EMP field and includes signals due to direct field penetration and pickup in the critical line length. This component might couple more than 100 A peak onto any individual signal lead.

Second is a slower pulse attributed in the test report to coupling to the exposed stub cable in the splice case, but could rise from any discontinuity in the sheath that is near exposed wires. This was predicted to be as high as 20 A at ringing frequencies in the MHz range. Third is the diffusion current described in Section 5.1.1. Conclusions from the T1 Carrier Study regarding these three stress levels are shown in Exhibit 5-6.

Response Component	Electromagnetic Environment	Peak Amplitude (amperes)	Pulse Characteristics	
High Frequency Early-Time Pulse	Central Office	130	Multiply Damped Sinusoid	
			Ringing Frequency	e-Folding Time
			15 MHz	2 μs
			30 MHz	100 ns
	Pole-Mounted Line Repeater	25	Multiply Damped Sinusoid	
			Ringing Frequency	e-Folding Time
			15,30 MHz	2 μs
			60,120 MHz	100 ns
	Manhole-Deployed Line Repeater	20	Bipolar Pulse	
			Rise Time	Pulse Width
			130 ns	500 ns
Slow Pulse	All (with buried cable)	20	Bipolar Pulse	
	All (with aerial cable)	untested	Rise Time	Pulse Width
			2 μs	5-20 μs
"Diffusion" Current	All (with buried cable)	2	Pulse	
	All (with aerial cable)	4	Rise Time	Pulse Width
			20 μs	40 μs

EXHIBIT 5-6. HEMP Threat To T1 Carrier Facilities, As Recorded In T1 Carrier Study Tests.

The second series of tests involved current-injection on signal leads, performed at Bell Labs. Double exponential (DE [50 ns rise-time]) and damped sinusoid (DS [10 ns rise-time]) pulses were injected.

Pulses ranging from 100 to 440 A were injected onto gas tube protected repeater and CO equipment leads; between 2 and 84 A were passed through the protector as a result. The only failures seen occurred at 300 A or more, levels above expected HEMP-induced stress levels. Exhibit 5-7 shows a table of equipment failure and nonfailure versus stress levels.

Unit type tested	Line Repeater 239B					Line FLF 1115XX	
Protection type used	SGSL					SGSL	
Type of pulse	DE	DS	DS	DE	DS	DE	DS
Peak pulse current per wire (into SGSL)	100 A	115 to 160 A	320 A	360 to 440 A	300 to 400A	195 A	200 A
Units tested	5	5	4	3	5	1	1
Failures	None	None	None	1	2	None	None

FLF: Fault Locate Filter
SGSL: Sealed Gas Surge Limiter
DE: Double Exponential
DS: Damped Sinusoid

EXHIBIT 5-7. T1 Carrier Repeater Current-Injection Tests At Bell Laboratories.

In related experiments, Sealed Gas Surge Limiters (SGSLs, or gas tube protectors), were tested separately to determine mean firing times and voltages. Results of tests conducted at HDL and at Boeing Aerospace Co. are shown in Exhibit 5-8(a) and (b). Typical PSN applications of the types tested are listed in Exhibit 5-9.

The worst-case HEMP stress coupled onto a signal line might rise as quickly as 10 V/ns at early times; test results show that if limiters fire, they do so within about 60 ns at about 600 to 700 V. An exception is the 208 A (the most commonly used in T1 repeaters), which fires at about 900 V.

Standard AT&T practices include lightning protection on above-ground T1 repeaters. From the TPD test data, repeater system test data, and current-coupling tests and analyses, it is reasonable to conclude that protected repeaters are not vulnerable to the 50 kV/m double-exponential pulse threat. The EMP survivability of repeaters without lightning protection is inconclusive. In current-injection tests, line repeaters failed when 38 to 50 A were passed through gas tube protectors. Testing and analysis indicate that surges of 20 A on buried lines and 40 A on aerial lines (damped sinusoids with ringing

SGSL	Mean Firing Time (ns)					Mean Firing Voltage (V)				
	Pulse Rise Times (V/ns)					Pulse Rise Times (V/ns)				
	2,000	100	50	25	16	2,000	100	50	25	16
200A	2.9	5.9	13.5	20.3	23.9	974	900	760	736	684
201A	3	5.1	12.4	17.3	22.3	589	581	692	660	680
205A	3	5	10.6	16	18.9	518	464	534	614	574
208A	3	6.3	18.5	22.7	31.3	1,160	1,080	1,020	907	933

(a). HDL

SGSL	Mean Firing Time (ns)					Mean Firing Voltage (V)				
	Pulse Rise Times (V/ns)					Pulse Rise Times (V/ns)				
	5,000	1,000	100	10	1	5,000	1,000	100	10	1
200A	1.4	2.8	9.0	61	432	2,417	1,395	850	684	531
201A	1.3	2.5	7.5	64	427	2,111	1,023	744	700	531
205A	1.3	2.5	6.1	56	294	1,880	794	560	565	324
208A	1.2	2	11.3	75.1	532.2	2,993	2,217	1,157	888	693

(b). Boeing Aerospace Co.

EXHIBIT 5-8. Gas Discharge Tube Test Results.

Type	Typical Application
200A	Existing T1 Carrier
301A	Outside Plant, Central Office
205A	5ESS Switch
208A	New T1 Carrier Installations

EXHIBIT 5-9. Typical Applications Of Gas Discharge Tubes In The PSN.

frequencies in the MHz range) can be nominally expected on signal lines at line repeaters; higher levels could couple in splice cases that happen to be poorly bonded or grounded.

5.1.3 EMP Effects On Central Office Equipment

For all T1 central office equipment, conventional mounting is in open bays (equipment racks). An important piece of office equipment is the channel bank (most commonly D4), which provides the voice-frequency interface to the digital line. The channel bank samples the analog voice-frequency signal, converts it to a PCM bit stream, and assembles the digitally encoded voice frequency signals from 24 voice channels and framing information into the 1.544 Mbits/s line signal. In the other transmission direction the channel bank provides the inverse functions.

A channel bank physically consists of shelves in an equipment frame filled with printed circuit boards. There are two basic types of circuit boards in the bank: channel units, devoted to functions involving individual voice channels; and common units, devoted to functions involving the digital line or entire bank. The voice-frequency pairs terminated at a channel unit are balanced to ground and may serve as either two-wire or four-wire circuits. Signaling is accomplished by various dc arrangements over the voice-frequency leads, or by separate signaling pairs. As a result, a single two-way voice-frequency circuit may have as many as eight pairs of leads at the channel bank interface. The common equipment boards supply maintenance and alarm functions, multiplexing functions, line and office interface functions, and certain other functions such as trunk processing and timing. Common equipment also includes high-frequency circuits, which provide the digital line interface.

In the T1 System, there is essentially no difference between office level stress and stress on line repeaters; as mentioned above, transients will not be propagated by repeaters. As with line repeaters, terminal equipment is either unprotected or protected against lightning and 60 Hz power faults. In a CO, protection may be gas-tube or 3 mil carbon block TPDs. Signal lines entering a building break out of the sheath and run to a Main Distribution Frame (MDF) where the lightning protection is located, then to equipment racks, which contain the office repeaters and channel banks.

Disregarding other office transients and direct coupling to the exposed leads, the currents induced on signal leads at the office would be the same as those at line repeaters. Consequently, tests similar to the line repeater tests were conducted at HDL on CO terminal equipment and on D4 channel banks. The AESOP and OSSI combination tests on protected line systems showed no failures, leading to the conclusion that the office repeaters can sustain up to 130 A simulated HEMP-induced transients without damage.

Under the T1 Carrier Study, an EMP-hardened D4 channel bank, enclosed in a shielded cabinet and protected by special TPDs at line interfaces, was subjected to simulated EMP fields and proved to be survivable. However, when the backplate and door of the shielded cabinet were left open, or when either the power or voice frequency (VF) TPDs were removed, hardware within the D4 channel bank suffered permanent failure. Because the equipment failed at the lowest field level (35 kV/m) attainable under the simulator at HDL, it was not possible to determine the actual failure threshold or to evaluate the success of alternative methods of protecting the channel bank.

A second test*, therefore, was undertaken to:

- identify the failure threshold for a D4 channel bank.
- identify and verify methods to protect a D4 channel bank.

The tests were conducted at the Air Force Weapons Laboratory (AFWL) using the ALECS facility, which produces a vertically-polarized electric field, adjustable in strength from 5 kV/m to 100 kV/m. The simulated EMP had a rise-time of between 3 and 15 ns and a decay-time of about 200 ns, comparable to the waveform expected from an actual EMP. To assess the channel bank's response to the simulator fields, tests of tone transmission, signal transmission, and idle circuit noise were made following each simulator pulse.

This study demonstrated that EMP affects a D4 channel bank primarily through the injection of large current transients at the interfaces to long connecting cables; fields of only 12 kV/m are sufficient to cause service-affecting hardware failures of unprotected D4 channel banks. EM fields are also coupled directly to wires on the backplane, but these transients are of a much lower amplitude than those at line interfaces. These transients will only cause damage if the field in the vicinity of the bank exceeds 40 kV/m, and only then if maximum coupling occurs to the backplane wires (i.e. the incident field must be planar and roughly parallel to the backplane wires).

* The "EMP Assessment of D4 Channel Bank," a study funded by the OMNCS and administered by DNA under Contract Number DNA001-85-C-0409.

The cables used during the testing of the D4 were typical of those found in many COs. The cables used were:

- Two power cables, each of 6-gauge wire.
- One alarm cable with four pairs of 26-gauge wire.
- Two ABAM 606B shielded T-carrier cables, each with 12 pairs of 22-gauge wire.
- Two VF cables, each with 100 pairs of 26-gauge wire.

The power, T-carrier, and alarm cables were bundled together and were separated horizontally by approximately six feet from the VF cable bundle.

It was assumed that the currents induced by EMP on cables connected to the D4 channel bank are comparable to those induced on similar cables connected to the 5ESS™ switch (see Section 6.2). The maximum current induced on the 128 twisted-pair cables connected to the 5ESS switch was 150 A, so a conservative estimate of 300 A was assumed as the maximum EMP-induced current on the cables connected to the D4 channel bank. At 50 kV/m, the vertical cables connected to the channel bank were adjusted until the current on all but the VF cables reached 300 A. Although 300 A could not be generated on the VF cables, the peak current of 15 A per pair going into the bank was comparable to the 12 A per pair expected in a CO environment.

A standard D4 channel bank without any EMP protection was pulsed 25 times at 5 kV/m without recording a single hardware failure. All channel units were tested at this level. An alarm control unit (ACU) was permanently damaged during the one test pulse at the 12 kV/m level, probably resulting from an over-current at the power interface. Based entirely on this one failure, it was concluded that the failure threshold of an unprotected D4 channel bank is between 5 kV/m and 12 kV/m vertical.

Exhibit 5-10 summarizes the failure thresholds of a standard, unhardened D4 channel bank in terms of the peak transient current induced at each line interface. For the Alarm, VF, and T-carrier interfaces, the induced currents are for each twisted pair.

Interface	Ip (A)	Risetime (ns)
Alarm	90	~ 70
VF	3	~ 70
T-carrier	13-27	75-85
Power	37	~ 55

Exhibit 5-10. Failure Thresholds of Unhardened D4 Channel Bank.

It was shown that the D4 channel bank could be protected against threat-level transients by installing TPDs at interfaces to external cables. The minimum protection needed at line interfaces to ensure survivability includes:

- Alarm Interface: 845A diodes.
- VF Interface: 0.01 μF capacitor.
- T-carrier Interface: 845A diodes.
- Power Interface: a 2 μH inductor and a 60 V voltage clamping diode.

With these TPDs in place, the bank survived 96 simulator pulses between 50 kV/m and 100 kV/m vertical.

Exhibit 5-11 summarizes the maximum induced transient currents at each of the line interfaces to the hardened D4 channel bank (using the EMP TPDs outlined above). For the Alarm, VF, and T-carrier interfaces, the induced currents are for each twisted pair. While these current transients did not cause the D4 to fail, they can be used as a conservative lower limit for the failure thresholds of each interface.

Interface	Ip (A)	Risetime (ns)
Alarm	177	95
VF	28	90
T-carrier	64	78
Power	247	90

Exhibit 5-11. Lower Limit Failure Thresholds for an EMP-Hardened D4 Channel Bank.

Further tests measured transient coupling to the backplane wires of the channel bank. The D4 was not connected to any cables other than to a short power cable, protected at the bank interface by a power TPD. To produce maximum coupling, the D4 was configured with no shielding cabinet and was oriented with the backplane wires parallel to the incident field. The D4 was subjected to 3 pulses at 40 kV/m vertical without failure. The same bank (protected on the shelves by EMP plug-in boards) was subjected to one pulse at 80 kV/m, and one channel unit lost its signaling capability. However, when the circuit packs of the channel unit were hardened, no failures were recorded in 3 pulses at the 80 kV/m level. It was concluded that the failure threshold due to direct radiation is between 40 kV/m and 80 kV/m vertical.

In the final test configuration, signal errors or interruptions occurred only twice in 33 tests, with durations of 0.1 ms and 10 ms. A synchronization signal was briefly lost in the remaining 94% of the tests, but its duration was not long enough to introduce errors into the data. The effect of these signal interruptions on voice communications was nearly imperceptible, although for data communications at 9600 baud, as many as 100 bits may be lost.

5.1.4 T1 System Response To EMP

As stated above, typical T1 cables and repeaters with standard (gas tube) protection against lightning and 60 Hz power faults are survivable against the 50 kV/m double exponential HEMP threat. The available test data on repeaters with no lightning protection indicates that the expected peak stress level (20A to 40A) and the measured susceptibility level (40A to 50A) are separated by less than the margin of error for this analysis; therefore, no conclusion can be drawn for unprotected repeaters.

D4 channel banks suffered significant damage and complete failure at transient stress levels that could occur in the central office environment. Fields of only 12 kV/m were sufficient to cause service-affecting failures of unprotected D4 channel banks. The failures were caused by the injection of large current transients (3 A - 90 A, ~ 70 ns rise-time) at the interfaces to long cables. By installing TPDs at these interfaces, the bank was able to withstand induced current transients at the various interfaces of between 28 A and 247 A (with rise-times of about 90 ns).

Based on these results, the unhardened T1 carrier sustem is vulnerable to the effects of HEMP. A hardened T1 carrier system, including EMP-protected D4 channel banks and repeaters, was subjected to threat-level fields, and is concluded to be robust to the effects of HEMP. A summary of experimental and predicted stress levels is presented in Exhibit 5-12.

5.2 FT3C MULTI-MODE OPTICAL-FIBER COMMUNICATIONS SYSTEM*

The FT3C system is a medium to high capacity trunk transmission system that transmits digitally-encoded voice and data information at 90 Mb/sec through multi-mode light pulses. The system contains three basic elements: the optical waveguide cable, the line repeater stations (LRSs) that regenerate the attenuated optical pulses, and the central office (CO) equipment that terminate and process the signal.

A typical FT3C lightwave system might be arranged as shown in Exhibit 5-13. The elements of an FT3C system cover a large geographic area; cable splices occur every 1 to 2 km, LRSs may be as far as 44 km apart, and the maintenance span between COs may reach 800 km. The impact of EMP on any part of the FT3C system must, therefore, take account of the total electromagnetic energy collected by long cable runs.

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* Significant portions of this section are drawn from NCS TIB 85-12 entitled, "FT3C Multimode Optical-Fiber Communications System: EMP Test and Assessment," one of two studies in a program funded by the OMNCS and administered by DNA under contract DAEA-18-75-A-0059-8Z01AC.

Equipment and Configuration	Test*	Levels Tested			Test Result	Worst-Case Levels Predicted during HEMP	
		Field	Current at Surge Protector	Current at Equipment Lead		Field	Current
D4 channel bank	Direct Illumination	12 kV/m	N/A	37 A•	Circuit Damage	50 kV/m	100 A at equipment lead••
D4 channel bank, with special EMP hardening**	Current Injection	N/A	250 A at TPD	1 A	upset***	N/A	100 A at TPD
Line Repeaters, typical, lightning power fault protected	Direct Illumination	80 kV/m	167 A at SGSL input	25 A	upset***	50 kV/m	40 A, aerial; 20 A, buried: at SGSL input
	Current Injection	N/A	260 A	40 A	upset***	N/A	
Line Repeaters, typical, unprotected and with various splice cases	untested	N/A	N/A	N/A	untested	50 kV/m	unknown; at least 20-40 A at equipment lead
Office Repeaters, typical, lightning and power fault protected	Direct Illumination	100 kV/m	200 A at SGSL input	30 A	upset***	50 kV/m	130 A at SGSL input
	Current Injection	N/A	200 A SGSL input	30 A	upset***	N/A	

* Direct Illumination was with AESOP and OSSI at HDL; Current Injection was with a 15 ns x 1 μs double exponential pulse or a damped sinusoidal pulse ringing at 30 MHz and folding in 1 μs at AT&T Bell Laboratories.

• An Alarm Control Unit (ACU) was permanently damaged at 12 kV/m, probably resulting from an overcurrent at the power interface. The damage threshold of the power interface was a 37 A current pulse with a rise-time of ~ 55 ns.

•• Lightning protection is installed a considerable distance from D4 inputs; 130 A could couple to wires leading directly to inputs.

** The experimental EMP-hardened channel bank used a special TPD.

*** All upsets were outages of << 1 second.

EXHIBIT 5-12. Comparison of Test Levels and Results with Stress Levels for T1 Carrier Equipment.

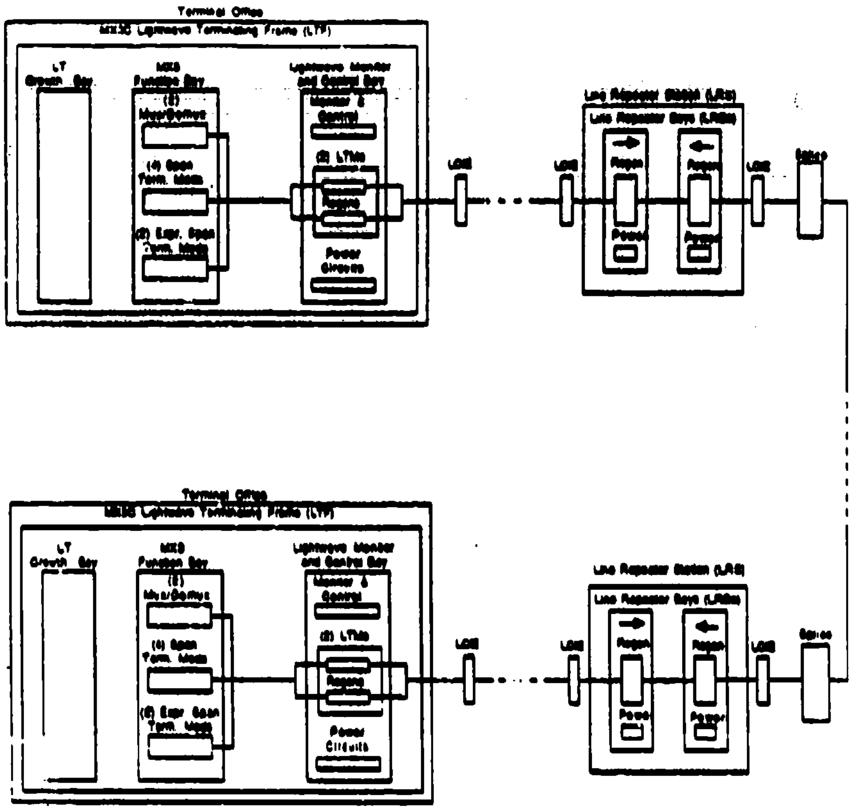


EXHIBIT 5-13. Typical FT3C System Configuration.

5.2.1 EMP Effects on the Cable

The glass fibers used in the FT3C system are very thin, each measuring only 0.125 mm (0.005 inch) in diameter. Individual fibers are grouped into ribbons of 12 fibers each, with up to 12 ribbons stacked together for a maximum of 144 fibers per cable. Up to 1344 voice circuits can be transmitted over a pair of lightguide fibers. The ribbons are intertwined to reduce the strain on the fibers due to cable bends, with steel wires incorporated to further distribute the load. The outer sheath contains two layers of high-density polyethylene, with 14 steel wires measuring 17 mils in diameter (approximately 26 gauge) imbedded in each layer. The two sets of wires are helically wrapped in the opposite sense from each other. Exhibit 5-14 shows a cross section of the LGA1-type lightguide cable used in the testing.

Because the complex configuration of the cable is difficult to model analytically, the only reliable, cost-effective way to quantify its response to HEMP is to physically test it. The optical fibers should not collect electromagnetic energy, so the analysis must focus on the sheath strength members. If the steel wires are modelled as a solid steel sheath, it is possible that current transients of 1-2 kA may be induced on the cable (see Section 4-5). Three different tests

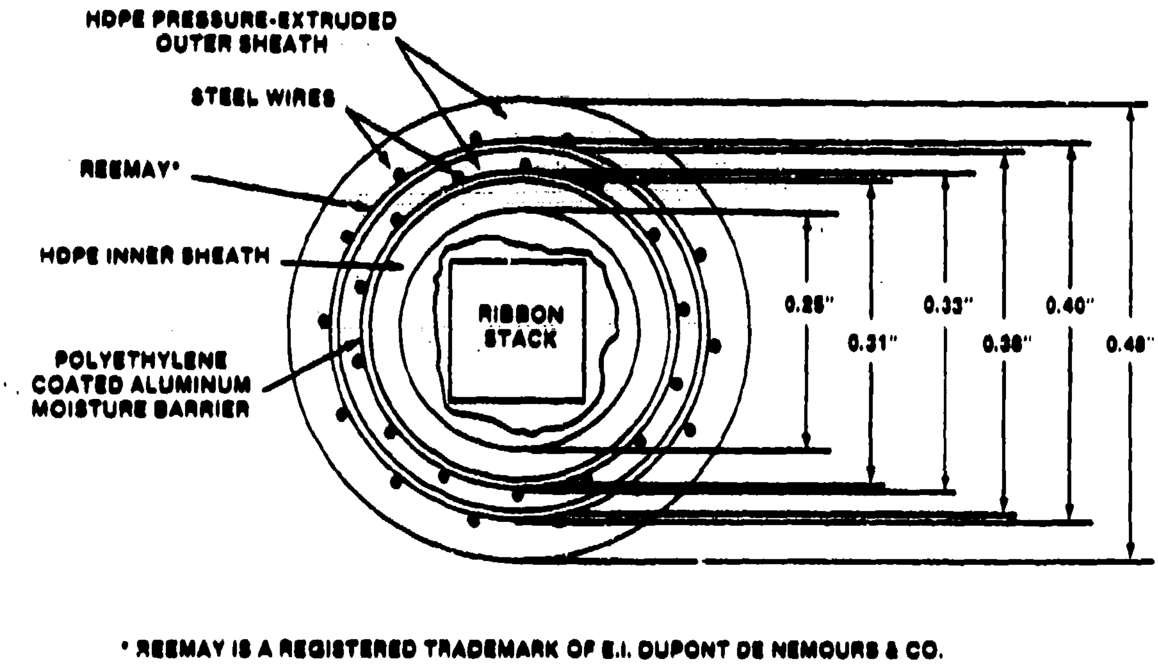


EXHIBIT 5-14. Cross-section of LGA1-type Lightguide Cable.

were conducted on the FT3C cable under the EMP simulator (AESOP) at HDL. While the FT3C is a buried system, the cable was tested on or above the ground to facilitate testing. Coupling to aerial cables is much more efficient than coupling to buried cables, so the transients that the aerial cable were exposed to had faster rise times, higher peak amplitudes, and more high-frequency components than the transients that an identical buried cable would have been exposed to. The incident field, therefore, induced worst-case transients on the cable.

The electromagnetic coupling test was designed to assist in the quantification of the relation between the incident electromagnetic field and the measured bulk cable current at low incident field levels. A 308-meter length of cable was laid parallel to the longitudinal axis of AESOP at a distance of 100 meters and was pulsed by the simulator. The peak incident electric field was about 2 kV/m at the cable center. The sheath termination hardware (STH) was alternately left open-circuited or grounded to a copper-clad iron rod, and in each case, the peak current generated at the cable's midpoint was about 27 A. Extrapolation of this low-level coupling predicts a peak induced current of about 700 A at the threat level of 50 kV/m horizontal.

The current-induction test was designed to produce the largest current AESOP could couple to the wire. With the cable carrying an optical signal in the near field of the simulator (8.5 m), a maximum current transient of 475 A was induced with the centerline grounded, below the predicted threat of 700 A. The test transient caused small "punch-through" holes on the outer sheath of the cable, possibly resulting from arcing from the steel wires inside the cable to earth ground. No parity errors or transmission path loss were measured. It is likely that this problem will worsen as currents reach threat levels, possibly causing signal disruption and permanent damage.

The third test measured the distribution of current within the cable. Results show that the outer steel wires carried about one-third of the cable current, with the inner steel wires and vapor barrier carrying the remaining two-thirds.

The AESOP simulator produces an electromagnetic field whose waveform and amplitude approximate those expected from a high-altitude nuclear burst. However, since the spacial extent over which these fields are produced are relatively limited, current injection must be used to reproduce current waveforms of the same magnitude as those induced by EMP on long cable runs.

If good bonding practices are not used, induced sheath currents may disrupt the optical signal or damage hardware components; one of the areas most likely to have poor bonding is cable splice points. Current injection was employed to assess the potential vulnerability of cable splice points to signal disruption. Exhibit 5-15 shows a typical optical splice organizer.

For testing purposes, the optical signal was looped through the cable splice and was monitored for parity errors. With the Marx generator charged to 90 kV, peak currents of 900 A were injected through cable stubs into the splice case, and no parity errors were detected. Although not explicitly stated, it is assumed that the stubs were configured with FT3C cable. It is also assumed that the rise and fall times of the injected current waveforms accurately represented EMP-induced transients.

The splice and optical cable were subjected to injected currents above the predicted threat level of 700 A, with no parity errors detected. It is likely that the 900 A injected current waveform caused some physical damage to the cable, because induced current transients of only 475 A were shown to cause minor damage to the outer sheath of the cable. Despite this, it appears that the cable and splice case are survivable to the effects of HEMP, because the optical signal was not disrupted due to the injected current.

5.2.2 EMP Effects on Line Repeater Stations

The LRS is designed to amplify and retransmit attenuated optical signals between CO facilities. Each LRS contains one or more Line Repeater Bays (LRBs), each of which can accommodate up to 48 FT3C regenerators, with one regenerator required for each direction of

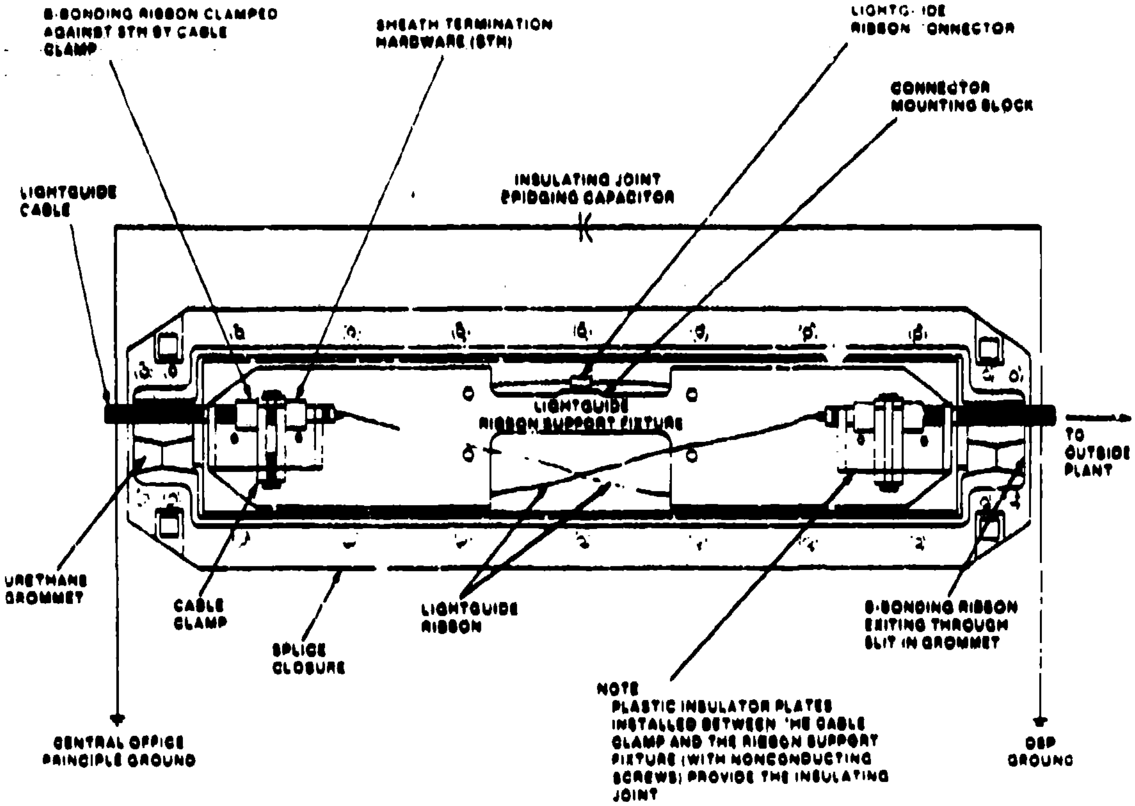


EXHIBIT 5-15. Grounding and Insulating Joint Connections on Lightguide Splice Organizer in a Vault Splice Closure and at a Central Office CEF.

transmission. The bays are powered by 131-type power converters, which require 208/240 V single-phase AC power input and produce -48 V DC power output for three fully-loaded LRBs. The power converters have a battery backup which can power three fully-loaded LRBs for about eight hours. Long lengths of cable are terminated at the LRS by lightguide cable interconnection equipment (LCIE). Exhibit 5-16 shows typical cable terminations on LCIE.

The large current transients that are generated on the steel strength-members of the FT3C cable may enter the LRS through the ground system (which incorporates both the LRS and the LCIE), because the current is terminated to ground through the LCIE. The FT3C power system may be susceptible to spurious shutdown or hardware damage when exposed to these transient ground-system currents.

During testing, the 131C power converters provided the -48 V DC power using one of its two rectifier circuits. While the equipment was exposed to the E-field produced by the Marx generators, an optical test signal was generated in the EMP shielded test hut, sent via a 100-foot long cable to the equipment being tested (where it was processed), and sent back to the test hut (where it was checked for parity errors). A maximum charge level of 78 kV produced average E-field components at the equipment of 55 kV/m horizontal and 25 kV/m vertical.

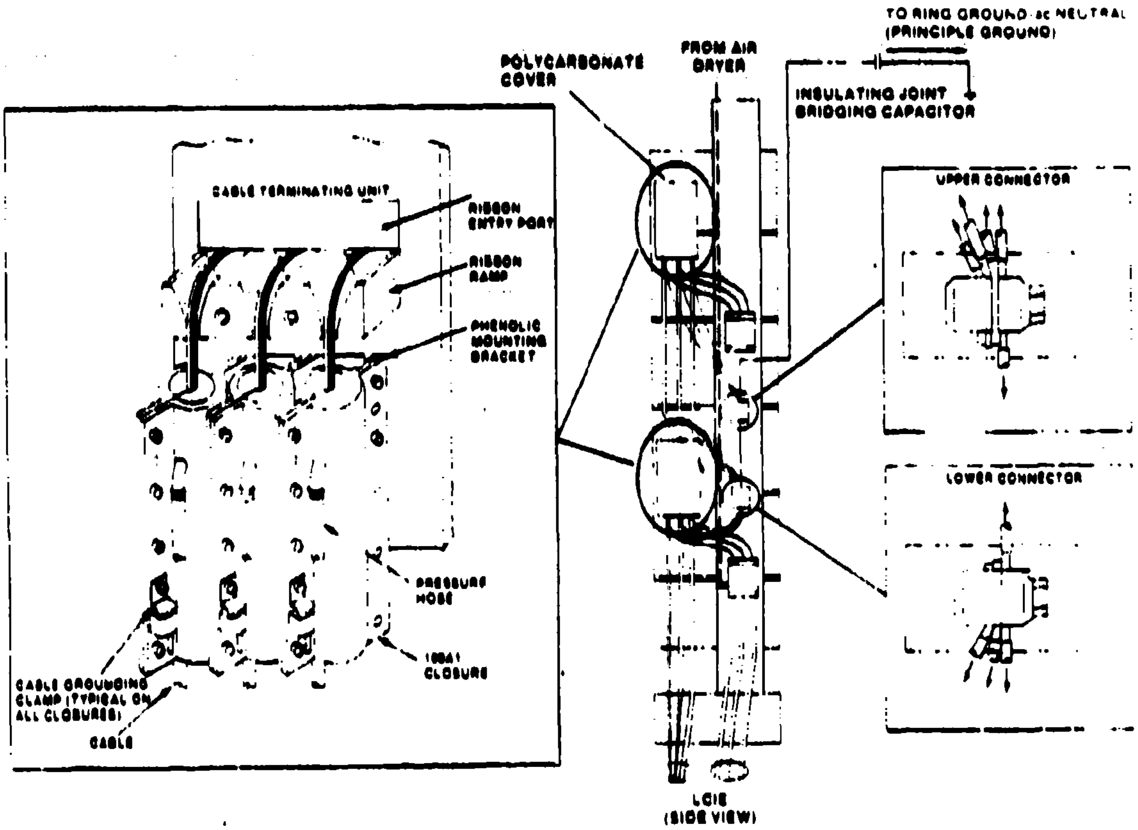


EXHIBIT 5-16. Detail Views of Cable Terminations on Lightguide Cable Interconnection Equipment.

The two major non-recoverable service-affecting failures that occurred during this phase of testing were:

- All three types of power units (131L1A, 131T1, and 131AB1) were subject to deactivation under EMP exposure, with the likelihood of disabling increasing with field intensity.

- One hardware failure occurred in a 131L1A power unit in the LRS at medium field-strength (55 kV charge level).

The deactivation of the power units constitutes a serious problem. When the power units deactivate, power is automatically supplied from the reserve batteries, which will continue to supply power until the deactivated power units are <u>manually</u> restarted. If the power units are not restarted within eight hours, the batteries will be drained, and all service will stop. It is evident that this power system is not survivable to EMP.

The failure of the 131L1A power unit potentially constitutes a more serious problem, because the failed unit needs to be repaired or replaced (not just restarted) within eight hours if uninterrupted service is to continue. Because only one power unit failed during the testing, and the failure occurred at medium field strength while no failures occurred at threat-level fields, the one recorded failure can be considered an anomaly and is not expected to occur during exposure to EMP-induced transients.

The power converter shutdowns during the testing of the LRS showed that the overvoltage protection circuitry of all three types of power converters were sensitive to RF noise. The problem was solved by placing a 0.1 μF capacitor between the gate and cathode of the SCR in the overvoltage protection circuitry and placing a 0.01 μF capacitor at the input lead of the overvoltage comparator. The maximum differential current across the supply and return leads of the power converters was shown to be about 40 A, leading to a peak voltage across the output terminals of about 4 kV. With the protective capacitors in place, the modified power converters withstood injected current waveforms with voltages exceeding 4 kV. Several further circuit modifications (similar to those mentioned above) enabled the power converters to withstand repeated peak incident fields of 70 kV/m horizontal and 20 kV/m vertical.

Although the modified power converters of this test configuration survived simulated EMP transients, they can not be considered survivable to HEMP. The shutdowns were traced to sensitivity of overvoltage protection circuitry to RF noise, yet this sensitivity was quite likely affected by the configuration of the test setup, which was different from typical LRSs and COs. A more thorough analysis using typical LRS and CO configurations is needed to verify that the modified power converters are survivable to HEMP.

Large EMP-induced current transients may be generated on the cable, leaving the lightguide cable interconnection equipment (LCIE), LRS, and CO equipment particularly vulnerable, because the LCIE terminates long lengths of cable at both the LRS and CO equipment bays. Because free-field simulation could not generate threat-level currents, current injection was chosen to assess the potential vulnerability of the LCIE to current transients.

With the Marx generator charged to 90 kV, a peak current of 600 A was generated in the LCIE (slightly below the predicted threat of 700 A), and no parity errors or hardware damage were detected. This current is lower than the current injected into the splice case at the same charging value, because the LCIE has a higher terminating impedance than the splice case. Since no signal disruptions or hardware damage occurred with 600 A of injected current, it is likely that the LCIE will survive injected threat-level currents, but this has yet to be verified.

Except for the damage and shutdown of the power converters, the LCIE and LRS suffered no service-affecting damage or upsets. However, it is possible for threat-level currents to enter the LRS through the ground system, which incorporates both the LCIE and the LRS. Since the survivability of this equipment against threat-level currents on the ground system has not been adequately addressed during testing, no assessment of the modified LRS' vulnerability to HEMP can be made.

The power converter shutdown problems incurred during simulator testing of the LRS are quite serious. After a power converter shutdown, power is always supplied by batteries, which last for only eight hours. If the power converters are not manually reactivated within eight hours, then the entire LRS which is powered by the affected power converter will be left without power, and no further calls can be processed. The power converters must therefore be considered vulnerable to HEMP. The survivability of LRS equipment is inconclusive, since threat-level currents were not injected into all subsystems.

5.2.3 EMP Effects on Central Office Equipment

The FT3C uses MX3 and MX3C equipment at all terminal locations (see Exhibit 5-13). The MX3C LTF consists of a single MX3C lightwave monitor and control bay, a lightwave terminating growth bay (as required), and from one to five MX3 function bays. Various modules may be installed in the MX3 function bay to allow the MX3C lightwave terminating frame (LTF) to operate in one or more of three modes. Each configuration of the MX3C LTF can terminate up to ten two-way FT3C lightwave service lines and up to two two-way FT3C lightwave protection lines. The monitor and control bay lightwave terminating module (LTM) provides an interface between the function bay modules and the optical cable. The regenerators within the LTM multiplex the two 45 Mb/sec input signals and output a 90 Mb/sec electrical signal. This signal drives the regenerator transmitter, which converts the signal to an FT3C lightwave line signal for transmission on the fibers. As with the LRS, long lengths of cable are terminated at the CO by lightguide cable interconnection equipment (LCIE).

In the FT3C system, there is essentially no difference between stress on central office equipment and stress on line repeaters. Consequently, tests similar to the line repeater tests were conducted at HDL on CO equipment.

During testing, CO equipment consisting of a monitor and control bay and a MX3 function bay were subjected to simulated EMP while powered by batteries. One of the two major non-recoverable service-affecting failures that occurred during the LRS testing affected the CO equipment as well: all 131-type power converters were again subject to deactivation (causing total service interruptions) when exposed to even low-level simulator pulses.

Threat-level currents can enter the CO equipment ground system from the cable through the LCIE. Because such currents were not injected into CO equipment, the same conclusion can be drawn here as was drawn for the LRSs: CO equipment with unmodified power converters is vulnerable to HEMP-induced transients, while no assessment of the vulnerability of the modified CO equipment can be made.

5.2.4 FT3C Multi-mode System Response to EMP

AESOP induced fields and injected threat-level currents did not produce any signal disruptions or service-affecting hardware damage during testing of the optical cable and splice case, so both elements appear survivable to the effects of HEMP.

Near threat-level currents were injected into the LCIE with no signal disruption or hardware damage detected, so it is likely that the LCIE will survive threat-level transients, but this has yet to be verified.

Unmodified power converters were shown to be vulnerable to simulated HEMP transients. Because both the LRS and CO rely on the power converters to power them, each must also be considered vulnerable to HEMP.

Although modified power converters were shown able to survive simulated HEMP fields, testing of the modified power converters did not use a LRS or CO configuration typical of those in the field; it is possible, therefore, that the modified power converters would not survive exposure to actual EMP. While current was injected directly into the LCIE and power converters, it was never injected into the LRS or CO equipment through an LCIE. These two problems cause the survivability of LRS and CO equipment to be inconclusive.

Because of the demonstrated vulnerability of the power system, the entire FT3C multi-mode system must be considered vulnerable to HEMP.

5.3 THE L4 AND L5 CARRIER SYSTEMS

The L4 System was introduced in the late 1960s for reliable high-capacity long-haul transmission. L4 is a solid-state system designed to survive in a nuclear environment (Ref. 22). All cable is buried, and hardened routes have buried main stations and repeaters.

The L4 System comprises cable, terminal office equipment, and three types of line repeaters: basic, regulating, and equalizing. Basic repeaters are nominally spaced 2 miles apart, regulating repeaters 12 miles, and equalizing repeaters 50 miles apart. Terminal stations (main stations, central offices) perform formatting and switching functions, allow remote control, and supply power to repeaters; they may be attended or unattended, and can be spaced up to 150 miles apart.

The L4 System was retrofitted over L3, introduced in 1953 with 12 coaxial tubes and 9,300 two-way voice channels, which, in turn, had been retrofitted over L2. In addition to carrying more tubes per sheath, each successive retrofit multiplexed higher frequencies and cut the previous nominal repeater spacing in half, for example, from 4 miles in L3, to 2 miles in L4.

The first commercial use of L5 was in 1974. L5 was planned for the relief of coaxial and radio systems along major north-south and east-west corridors in intercity networks (Ref. 20). The L5 system is retrofitted on L4, and has basic repeaters every mile. Main stations perform the same functions as L4 main stations, but must be spaced 75 miles apart or less.

A high-level block diagram of system terminal equipment is shown in Exhibit 5-17. Main station equipment includes transmitting and receiving equalizing repeaters and multiplexing equipment for customer message formatting and amplification. Additionally, main station L4 and L5 equipment performs automatic protection switching, remote monitoring and control, fault location, and power supply.

5.3.1 EMP Effects On The Cables

L4 trunks generally are 3-inch shielded cable carrying 20 coaxial tubes and 52 interstitial service pairs. Each coaxial tube carries six frequency-multiplexed master groups, i.e., 3,600 one-way voice channels; each pair carries 3,600 two-way (full-duplex) voice channels. Of the 20 tubes, one pair is spare and nine pairs are used, supplying 32,400 two-way message channels per sheath. Exhibit 5-18 shows a typical L4 cable.

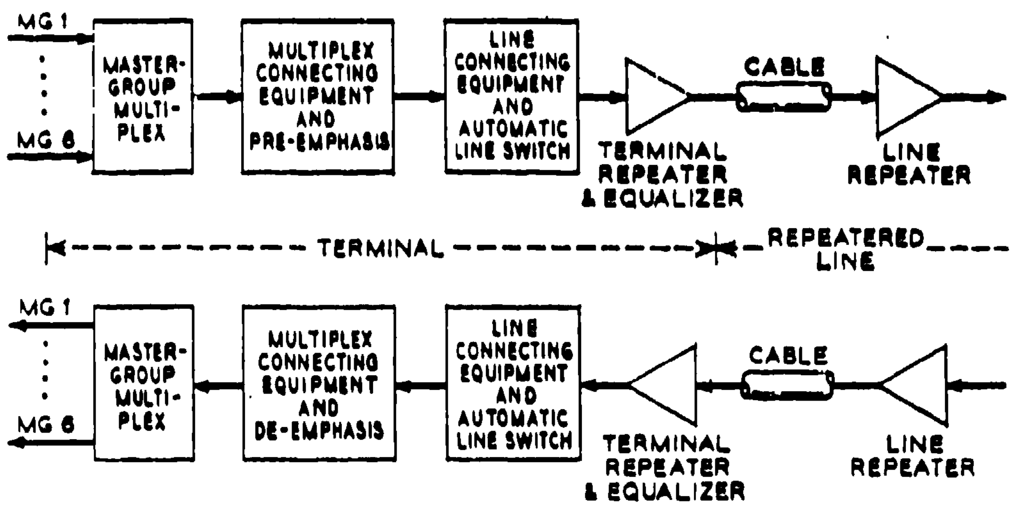
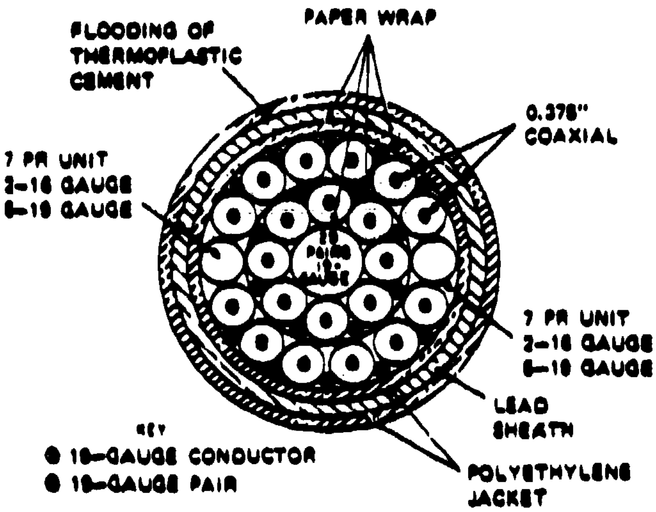


EXHIBIT 5-17. Simplified Block Diagram Of L4 Terminal Equipment.

L5 multiplexes three full-duplex jumbogroups (each comprising six mastergroups) per coaxial pair. When new cable is laid, it contains 22 tubes (two are still spare) supplying a total 108,000 two-way voice channels per sheath.



Trunk cable: WECo "COAX-20", buried, pressurized with dry air.
Standard coaxial line: 0.1" copper conductor insulated from 0.375" cylindrical conductor of 0.012" copper tape seamed lengthwise. Outer conductor wrapped in one or two 0.006" steel tapes for added strength and H field shielding.
Completed trunk cable core (including core pairs, inner eight coaxials, interstice pairs, outer 12 coaxials, two units of wire pairs, interstice single wires, paper wrapping): 2.13" diameter.
Inner polyethylene jacket: 0.075" thick.
Outer paper wrap (heat barrier): spirally wound, thickness 0.005".
Lead (Pb) sheath: Thickness 0.112", conductivity is 4.5 x 10^6 mho/m.
Outer polyethylene jacket: 0.079" thick black polyethylene, dielectric constant is 2.3.
Total cable outer diameter: 2.972."

EXHIBIT 5-18. Typical L4 Cable Characteristics.

In addition to the 6 and 18 mastergroups that L4 and L5 trunks respectively carry, they carry line pilot signals, equalizer test and remote control adjustment signals, line-switching signals, command carrier signals, and monitoring oscillator signals. Diagrams of L4, L5 system frequency allocation are shown in Exhibit 5-19(a) and (b).

If L cables were exposed to EMP, major concerns would be similar to those for T1 cable: direct damage from large currents, diffusion currents on signal conductors, and high-frequency coupling to exposed cable. However, there are a few differences. Since L systems are analog and repeaters actually amplify signals, the potential amplification of high-frequency HEMP-induced surges is a concern. Additionally, lower-frequency surges could sum along entire 150-mile lengths, since repeater dc power is sent along signal lines and power separation filters are designed to pass low frequencies along the line.

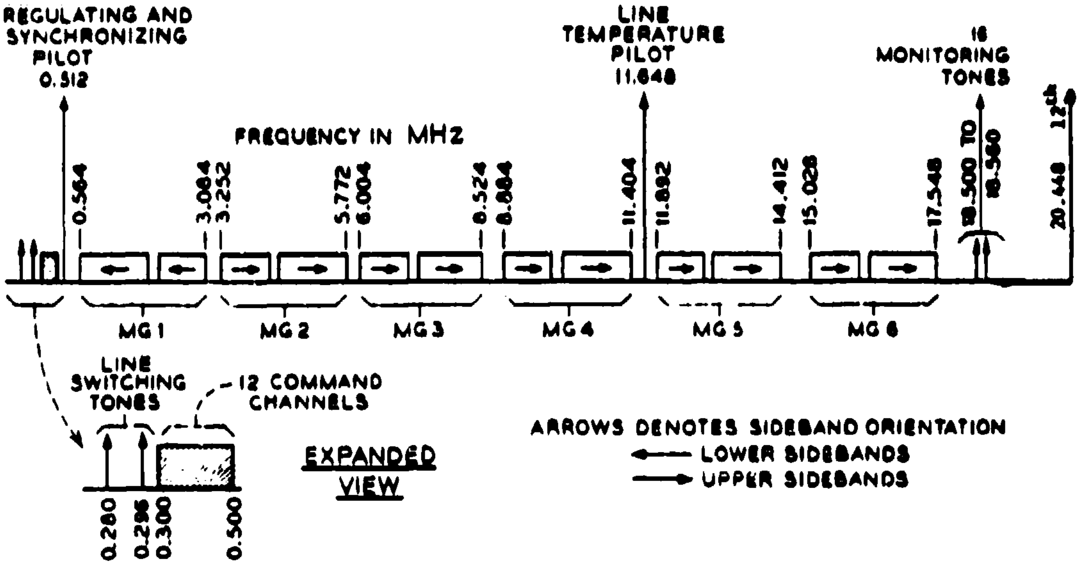
In general, L4 cables are well-protected against direct coupling and its effects. There are no splice cases at repeaters; signal lines in L4 are much less apt to be exposed to sheath currents than signal lines in twisted pair cables or in T1, for example. All lines are buried.

On some routes, guard wires are buried with the cables; guard wires are two 0.165-inch diameter wires, 10 inches apart and 24 inches above the cable. The purpose of these wires is to protect cables from direct lightning strikes. The cables are better conductors and carry 90 percent of induced currents at frequencies above 10 kHz (rise times less than 25 μs), where most HEMP energy is radiated.

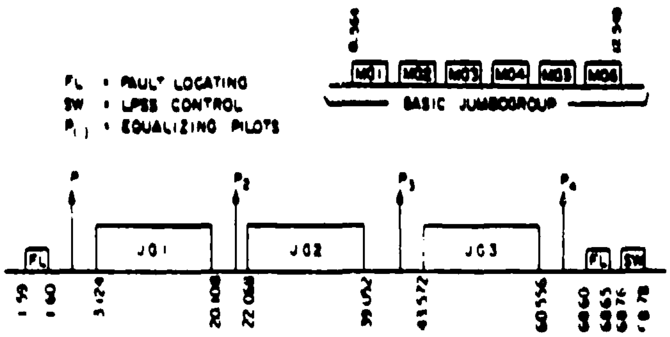
5.3.2 EMP Effects On Repeaters

Over a 4,000-mile route, signal loss is 120,000 dB in L4 cable at nominal L4 frequencies. The L4 system is designed to deliver signals to within $\pm$ 3 dB amplitude for all circuits. Amplification of the signal is a complex task and must be well controlled. Control of the signal levels is accomplished by three types of repeaters. The basic repeater is a plug-in unit with a shaped gain-frequency characteristic that compensates for two miles of 0.375-inch coaxial cable loss at 55 F. A regulating repeater performs the basic repeater function and provides gain regulation to compensate for changes in cable loss due to variations in soil ambient temperature. An equalizing (mid-span) repeater performs the regulating repeater functions and provides equalization across the L4 band using six networks whose characteristics can be varied remotely by commands from a main station control center.

Each repeater has power separation filters (PSFs), a Zener diode for constant voltage drop, and an amplifier circuit. The PSFs supply dc power to the amplifiers and divert frequencies below 70 kHz from amplification. A preamplifier, which accepts frequencies over 100 kHz, and a power amplifier amplify the analog signal, and are separated by Line Build-Out units (LBOs). LBOs are passive lossy networks that mimic cable losses; they are inserted (in 0.1-mile increments) when



(a). L4 frequency allocation



(b). L5 frequency allocation

EXHIBIT 5-19. L System Frequency Allocation.

cables are shorter than nominal. A block diagram of a basic repeater, showing the power separation filters, is shown in Exhibit 5-20. Typical repeater layout according to function is shown for L4 and L5 in Exhibit 5-21.

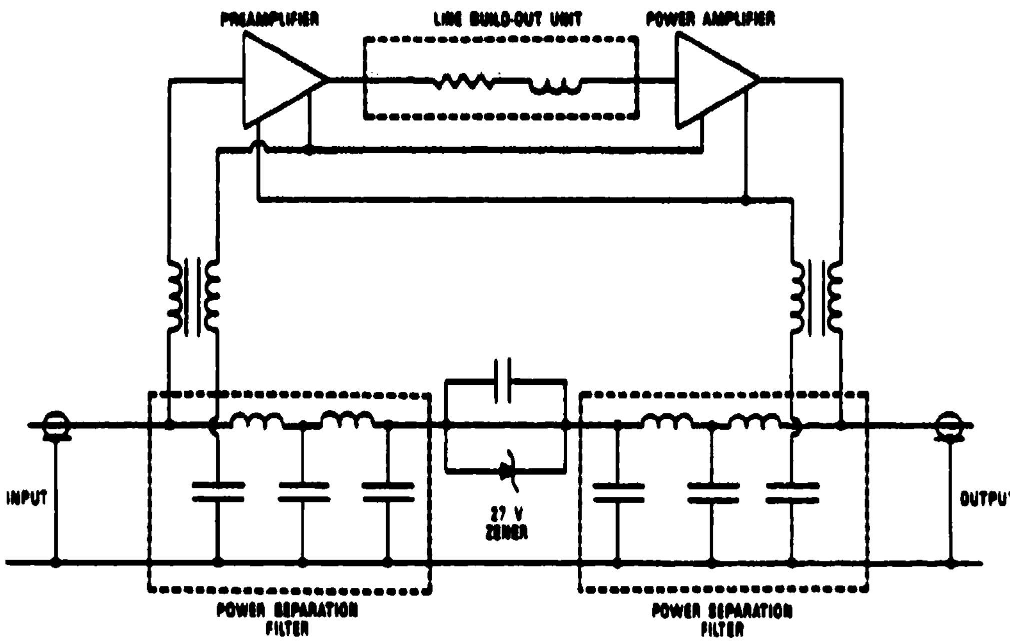


EXHIBIT 5-20. Simplified Schematic Of L4 Basic Repeater.

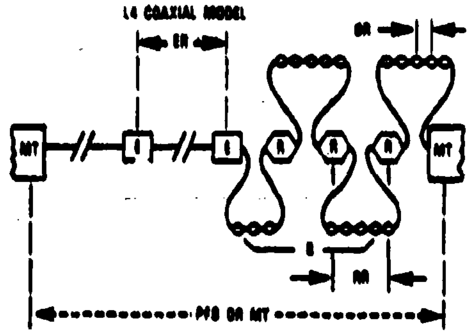
In general, L4 repeaters (in and out of main stations) are well protected. Transient protection and transformers exist on all interface circuitry. Repeaters have heavy aluminum cases, and are installed in manholes. Protective grounding circuits may also exist at repeater sites.

Because of the configuration of the 150-mile repeater power supply loop, repeaters near the ends of the loop operate at high potentials with respect to ground. This makes high potential surges an even greater concern. L systems do not use TPDs on signal lines (which also carry repeater power); lines terminate in the repeater power separation filter, which is exposed directly to diffusion currents. Nonetheless, L4 repeaters are designed to withstand induced EMP surges, especially along hardened routes--a requirement that may have had the greatest influence on repeater physical design and circuit design.

MODEL / MILES*	L4 COAXIAL AVG.	L4 COAXIAL MAX	L5 COAXIAL AVG.	L5 COAXIAL MAX
BASIC RPTR (BR)	2	2	1	1
REGULATING RPTR (RR)	12	12	6	7
EQUALIZING RPTR (ER)	44	64	30	38
POWER FEED (PF)	-	-	60	75
POWER FEED/SWITCH (PFS)	120	160	120	150
MAIN TERMINAL (MT)	120	*	240	*

SYSTEM CAPACITIES	L4			L5		
NO. COAX PAIRS	12	20	22	12	18	22
NO. MGS	30	54	60	90	144	180
NO. 4 kHz	10,800	32,400	36,000	54,000	86,400	108,000

*BASED ON THE NATIONAL AVERAGE



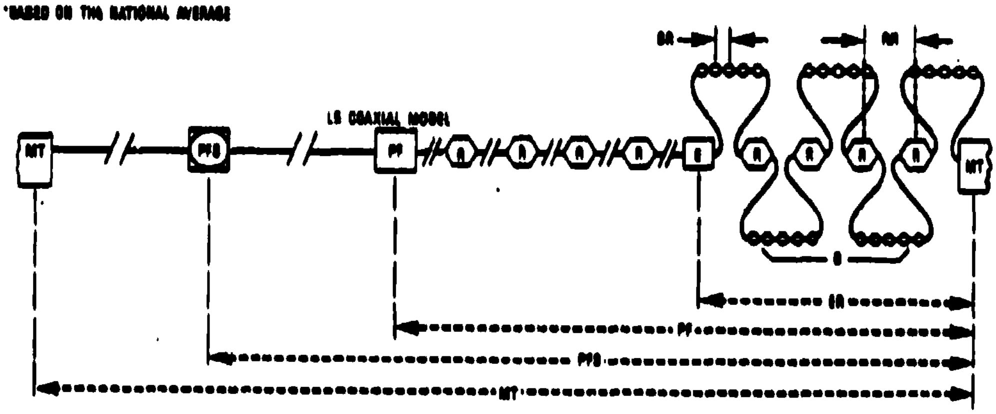


EXHIBIT 5-21   L System Repeater Spacing.

The low-pass PSF has its break point at 70 kHz in line repeaters and 40 kHz in main office repeaters. High-frequency signals are sent to the preamplifier input filter, a high-pass filter with its break point at 100 kHz in line repeaters and 45 kHz in office repeaters. Low-frequency signals are passed to the power supply circuit and directly to the repeater Zener diode. Thus, pulse components below 100 kHz could stress the diode and the preamplifier filter, but they will not be amplified.

Pulses entering through the output terminals are similarly filtered and passed to the power amplifier output. The preamplifier input and power amplifier output are well-protected; the preamplifier input has a transformer and surge protection diodes, and the power amplifier output has a transformer and an RLC filter (Ref. 23). At 20 MHz the pre-amplifier has a gain of 6 to 17 dB, the power amplifier a gain of 18 to 20 dB (Ref. 23).

Protective silicon diodes are installed across both the primary and secondary windings of the preamplifier input transformer. The preamplifier first stage transistor would be damaged if exposed to too much voltage drop; the protection diodes are designed to limit voltage spikes to a swing of 2 V peak-to-peak for any type of transient, including EMP.

This combination of repeater protection has proved effective against short circuits, lightning, and 800 V, 60 Hz power fault transients. Before deployment in L4 systems, repeaters are tested with transients peaking at 2 kV in 10 μs with up to a millisecond duration injected onto input and output terminals.

Repeater cases are thick aluminum, which is an effective shield. Cases and cables are grounded on a ground bus, which runs to a peripheral ground of 0.75-inch bonded copper-weld rods buried around the manhole. At the repeaters and all along the cable, signal conductors see an estimated 6,000 Ω impedance to their return (the coaxial tubes), essentially an open circuit compared with their 75 Ω source impedance. Thus, they are essentially 150-mile conductors with a continual open circuit to ground. The outer coaxial tubes, on the other hand, are bonded to the lead (Pb) sheath at each repeater, effectively grounding them every two miles. Additionally, cables are laid inside steel pipe for 30 feet as they approach a repeater on each end.

These are good bonding practices, as outlined in Chapter 4. Extremely high surge currents might reflect somewhat from the ground bus onto coaxial tubes, but would not be significantly propagated down the line. Ringing that couples onto signal lines would either be damped by amplifier transformers (if high-frequency) or attenuated by the 150-mile isolated signal lead itself (if low-frequency).

Bulk current injected onto the trunk sheath was 1,460 A, somewhat less than the 2 kA that might couple to buried cable. Free-field illumination levels of all equipment were up to 80 kV/m, much higher than the 50 kV/m threat. In addition, equipment was exposed to repetitive pulses of free-field illumination and current injection, spaced 0.5 μs apart, to simulate multiple HEMP events.

Thus far, the coupling of transient fields to trunk sheaths and the integration of diffused currents over long lines have been discussed, including attenuation by repeater transformers, but ignoring repeater action. In the L4 System, there is also concern about the propagation and amplification of high-frequency (above 100 kHz) surges down the line.

Such limiting action causes a burst of noise to be propagated through the system. In tests, this noise was enough to cause temporary loss of signal to the next repeater in line, but did not cause any damage. Since any amplification of this noise would be attenuated by the next interrepeater cable length, PSF, and preamplifier input filter, it is concluded that high-frequency noise may be spread over time, but it will not be amplified above the level seen at a single repeater.

5.3.3 EMP Effects On Central Office Equipment

Central offices perform remote control of line systems, protection switching on all transmission trunks, and protective grounding and shutdown of the repeater power supply loop.

A control center, located only at certain main stations, is attended and allows performance of remote temperature and gain sensing, adjustment of equalizers, problem location, and interrogation and control of other (slave) main stations, which need not be attended. As an example, problem location might be conducted by remotely turning on test oscillators present in each equalizer and monitoring oscillators present in each repeater. Signal levels would be displayed in a spectrum analyzer at the control center, and amplifier gain deviations would be pinpointed.

Automatic protection switching occurs at each main station, staffed or unstaffed. When a line pilot used for primary frequency synchronization or repeater gain regulation deviates from preset levels, all circuits on that coaxial tube are switched onto the standby pair at the receiving end, and a line protection switching tone is sent to the transmitting end. Any upset in the line pilot tone causes the Line Protection Switching System (LPSS) to switch the standby pair of coaxial tubes into the transmission path.

Main stations contain high-voltage dc converters that furnish power to line repeaters over the center conductor of the coaxial lines and to other remote equipment over the interstitial lines. A line repeater loop (two main terminals and all of the line repeaters between them) is powered from both ends, with one end grounded and one end floating. The potential drop along each long line is symmetric with respect to ground, one end positive and one negative. In L4 the long-line drop over 150 miles is 3,600 V, maintaining 520 mA dc; in L5 the drop over 75 miles is 1,150 V, maintaining 910 mA.

Induced sheath currents or earth potential gradients can cause dangerously high voltages at the floating end of the loop, so a protective earth grounding circuit is tied to floating ground. A block diagram of the L4 repeater power supply loop is shown in Exhibit 5-22, and simpler block diagrams of the grounding protection are shown for L4 and L5 in Exhibit 5-23(a) and (b).

As mentioned in the previous section, surge transients at COs would be equivalent to those expected at rapeaters at the ends of a 150-mile segment.

On each L4 signal line entering a main station building, surge protection or regulator diodes and a spark gap are provided. Typical spark gaps used are Western Electric (WECo) type 98, 111, or 123 carbon blocks. As part numbers ascend, these carbon blocks are built to carry more current; plant engineers choose a part based on experience with transient problems in their areas. Special high-current protectors, such as WECo 1J8, may be installed where severe power-fault transients could couple to signal lines.

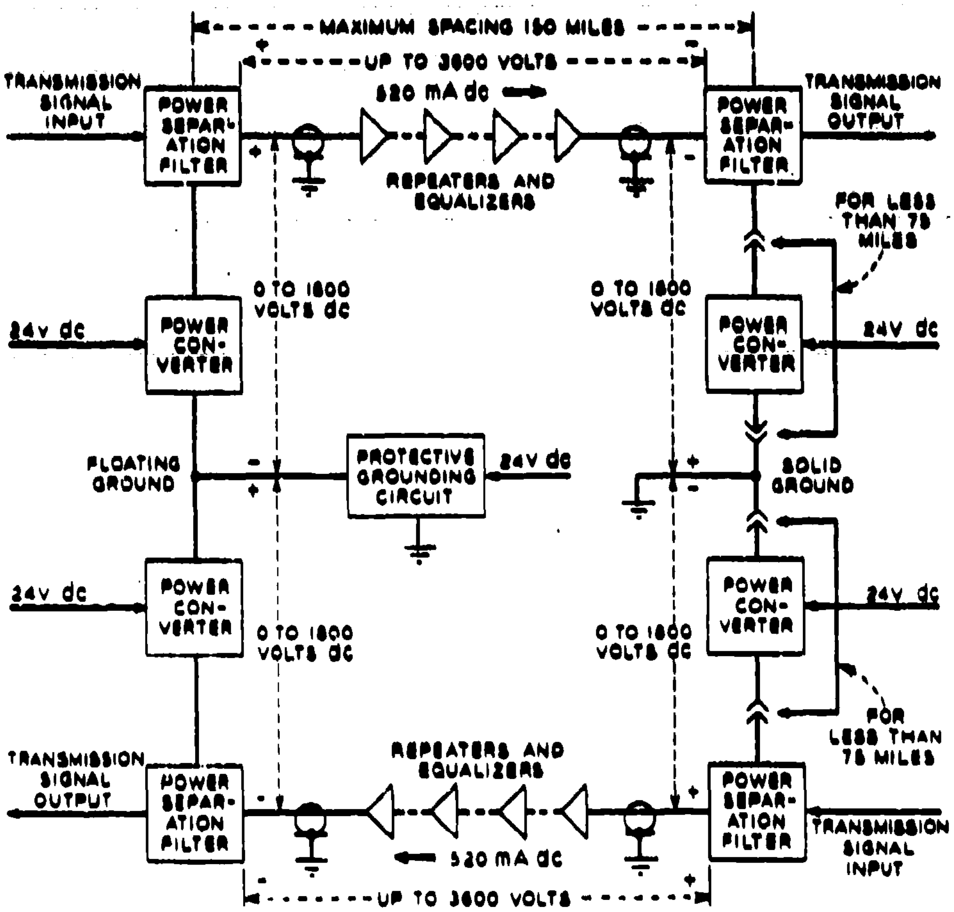
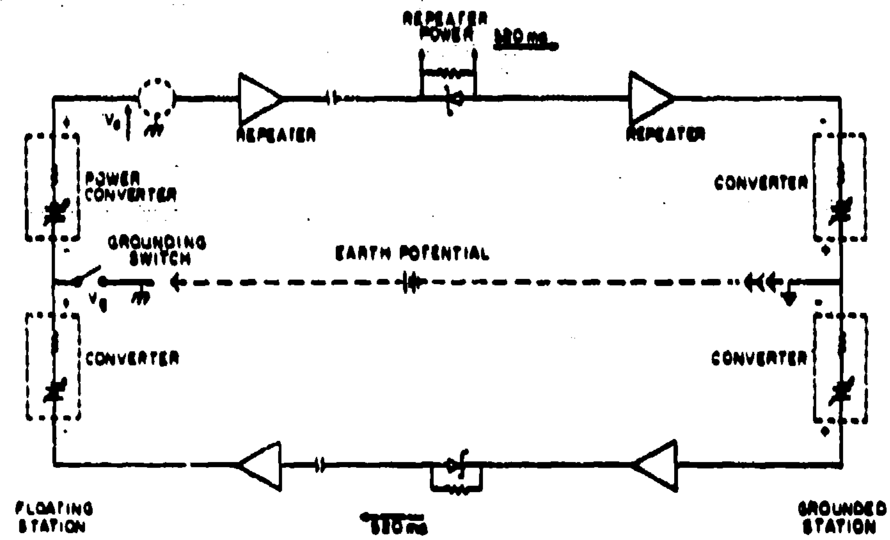
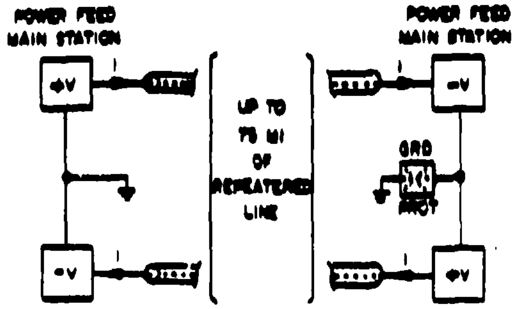


EXHIBIT 5-22. L4 Repeater Power Supply Loop Block Diagram.

Firing tests of the typical spark gaps in use on L4 lines were conducted at Bell Labs. (Data are from Reference 22.) Two pulse types were tested. The first rose to peak in 4 μs; in two series of tests, the mean and standard deviation firing voltages were 610 $\pm$ 70 V and 780 $\pm$ 140 V. The second pulse was the 10 μs x 1,000 μs pulse that repeaters are tested with; the observed firing voltage was 700 $\pm$ 75 V. For all tests combined, the average delay (charging of the carbon blocks) was 7 ns to 40 ns at voltages near the threshold (representing the worst case), and 5 to 7 ns at high voltages up to 2,000 V. From these tests, it is apparent that all current in the pulse for at least the first few nanoseconds will be passed on the lines directly into equipment leads.



(a). L4



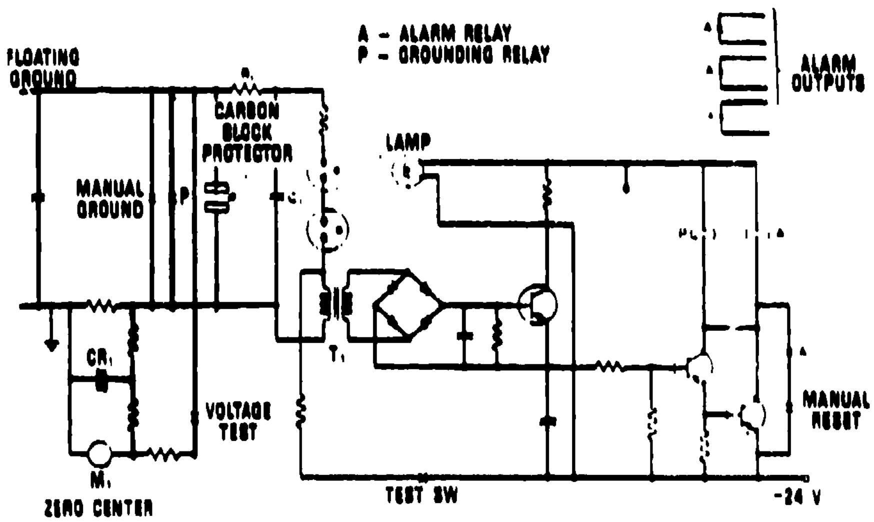
(b). L5

EXHIBIT 5-23. L System Repeater Power Grounding Protection.

As mentioned, there is a protective circuit on the repeater power loop floating ground point to protect against induced surges and earth potentials. A schematic and listing of the operational limits of this circuit are shown in Exhibit 5-24. Central offices have additional threats to this power supply loop, particularly from magnetohydrodynamic EMP (MHD EMP).*

Shutdown of the power loops through the protective grounding circuit or the power converters is not a failure; it is a protective loss of power that requires manual intervention. Personnel at the two central offices would have to be in communication to raise the four power converters to operational level in tandem. This communication normally takes place over order wires, the two groups of wires that run in L4 cables near the outer sheath in place of coaxial tubes (see the L4 cross-section, Exhibit 5-18).

Communication between PSN personnel is voice frequency analog repeated at the equalizing repeaters only (in separate amplification circuits from signal amplifiers at the repeaters).



PEAK INSTANTANEOUS LIMIT	**2,800 V TOTAL**
PEAK FLOATING GROUND VOLTAGE	**800 V MAXIMUM**
MAXIMUM STEADY-STATE OVER-VOLTAGE	**2,200 V TOTAL**
MAXIMUM STEADY-STATE FLOATING GROUND VOLTAGE	**400 V MAXIMUM**
STEADY-STATE SHUTDOWN LIMIT FOR FLOATING GROUND VOLTAGE	**3[illegible] V**
DELAY TIME FOR STEADY-STATE SHUTDOWN	**20 MS.**

EXHIBIT 5-24. Schematic And Limits Of Power Loop Protective Grounding Circuit.

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* MHD EMP results in an induced potential over the surface of the Earth and is a natural corollary to HEMP.

The second potential problem is firing of spark gaps on the separate amplifier power supply lines, latch-up, and blowing of the fuses. This would mean that power to the 150-mile loop of L4 signal repeaters could not be restored unless personnel could communicate over other routes, or replace the fuses in the field.

5.3.4 Response Of The L4/L5 Carrier Systems To EMP

In addition to the cable current, direct illumination and earth potential stresses, current will be carried to L4 COs along other building penetrations as described in Chapter 4. Some analytically predicted levels (Ref. 24) are listed in Exhibit 5-25.

A typical L4 system is sometimes considered to be a link in a hardened route. Along such a route, cable is hardened to sustain 150 psi overpressure from blast, repeaters to sustain 50 psi, and COs 10 psi. From information available on construction and installation practices along such routes, a typical system as a whole appears to be well-protected. Neither conducted stresses on penetrators nor direct illumination fields are expected to cause failures. This expectation is consistent with test results; no tested L4 component has been determined to fail at full stress levels. The most serious problems observed have been power or transmission outages for a half second, and power loop automatic protection shutdown, requiring manual intervention.

Penetration	Main Station AMPS PK-PK	Repeater Station AMPS PK-PK
Power Cables	2900	-
Aerial Telephone Cable	5200	-
Buried L-4 Cable	1000	1000
Sewer/Water Pipes	1000	-

EXHIBIT 5-25. Analytically Predicted Penetrator Currents.

5.4 MICROWAVE RADIO SYSTEMS

Long-haul transmission systems frequently use line-of-sight microwave radio. It was estimated in 1977 that 60 percent of the circuit-miles in the AT&T toll network were microwave links (Ref. 20).

Radio systems, like cable transmission systems, are made up of switching and signaling equipment in central offices, and repeater sites for amplification on long-haul lines. A microwave radio link junction consists of a structural steel tower holding transmitting and receiving antennas, waveguides that run down the tower to a building, and interface, protection, modulation, and multiplexing equipment (or the inverse) inside the building.

The most common radio systems in the PSN are Frequency Division Multiplexed - Frequency Modulation (FDM-FM) systems, which carry analog signals in the GHz frequencies. The most important of these are the TD Systems, notably TD-2. TD-2 uses vacuum-tube technology, multiplexes 1,500 circuits per radio channel on vertically and horizontally-polarized beams (with interstice channels of the other polarization), and uses horn reflector antennas. Frequency range is 3.7 to 4.2 GHz; average repeater spacing is 26 miles and is decreasing (as circuits per channel increase). The solid-state version, TD-3, is replacing TD-2 on an evolutionary basis.

Another class of FDM-FM analog systems are the TH systems, notably TH-1. It transmits over the 5.925 to 6.425 GHz range, but is otherwise similar to the TD systems. TH-3, the solid-state version, is similarly replacing existing TH-1 systems. TH-3 is expected to carry up to 2,400 circuits per radio channel.

Other bands exist centered around 11 and 18 GHz, but the higher frequencies are more problematic. The 11 GHz band is limited to short-haul traffic, but links can be used as extensions in congested areas or as stand-by protection routes. New technology is evolving here at higher frequencies, in SSB (single side-band) radio, and in data transmission at lower frequencies.

As mentioned, equipment is housed in ordinary buildings near the microwave tower. Radio transmitters and receivers are usually located as close to the tower as possible to minimize waveguide losses, and, consequently, there may be up to another 1,000 feet of coaxial cable leading to multiplex equipment terminals.

Similar to cable systems, FM systems include protection switching in event of equipment failure. Protection (idle) channels can be switched into the normal transmission path. In addition, patch bays are located at end stations (main stations) for restoration and routing flexibility.

5.4.1 Diffusion And Penetration Stresses

The analysis of penetration stresses entering a building from the microwave tower and waveguide run was discussed in Section 4.3.4. A worst-case assessment determined that 6 kA peak-to-peak EMP currents are expected at the waveguide point of entry into a building. Rise times of 100 to 400 ns for typical tower heights in the Bell system are expected. The rate of rise of current for the worst case is thus determined to be 60 A/ns. Typical lightning transients expected by radio station designers are 10 kA tower currents with 1 μs rise times (Ref. 25). The rate of rise in this case is 10 A/ns, which is comparable to the EMP rate of rise.

The applied practice of bonding and grounding waveguides and ac power conduits at the building entrance to external and internal ring grounds provides a significant reduction in transients on penetrators. Testing (Ref. 8) has shown that for signal leads within 10 feet of the penetrator (near zone), induced signals can be reduced by 45 dB or more using this practice. For leads that are farther away than 10 feet (far zone), induced transients can be reduced by more than 65 dB. The transient currents expected in this case are 3 A and 34 A on leads in the far and near zones, respectively. In particular, the coaxial communication cable (in the near zone) connecting the waveguide to the radio bays can carry over 30 A. Such large currents require waveguides and coaxial cables extending 10 feet or more inside a large station have multiple grounds inside the building. They should also be multiply grounded at all entrances to equipment rooms.

Power line leads are also expected to produce about 1 A of induced current (see Section 6.2.2) at radio equipment leads. Other penetrators such as water pipes, sewer pipes, fuel lines, and conduits for external lighting are not expected to contribute much current, since these penetrations are usually not routed near equipment bays.

Diffusion fields are also expected to induce significant interbay currents as discussed briefly in Section 4.4. Simulated HEMP tests have been conducted by Bell Labs on TD-2 microwave relays at several sites (Refs. 26, 27, 28). The microwave terminal equipment tested includes TD-2 radio bays, protection switching circuits, and multiplexer/demultiplexer subsystems. Exhibit 5-26 lists the test sites used in these studies.

5.4.2 System Response to HEMP

The assessment of the survivability of microwave systems requires a consideration of penetration currents coupling to radio equipments, multiplexers, and protection switching, as well as diffusion coupling from direct illumination. The present test data base indicates that the TD-2 microwave equipment is survivable to direct illumination to HEMP fields of 50 kV/m. However, this testing did not simulate the direct penetration current expected from the tower and waveguide. Although, the currents induced by direct illumination are less than 2 A, penetration currents (due to tower transients) can be 30 to 40 A. This suggests that the total stress on microwave equipment will be substantially greater than levels tested to date. Actual stress levels at particular sites, of course, are dependent on placement of equipment racks (near or far zone) and interior routing of other conductors (i.e., power lines, telephone lines, AM/FM antennas). Tests performed during the PREMPT (Ref. 45) program provided some data concerning damage thresholds for some typical radio and multiplex equipment ranging from 9 A to 110 A.

In summary, test data indicate that TD-2 microwave systems are not vulnerable to permanent damage from direct illumination or diffused fields. The dominant conducted stress (potentially damaging) would most likely occur from tower transients. However, the abundance of microwave and radio towers in the PSN and relatively frequent occurrence of lightning transients has led to design practices (i.e., bonding and grounding) that mitigate these surges which have rates of rise comparable to that of HEMP. It is inferred that TD-2 systems are therefore survivable to HEMP conducted and diffuse transients.

Location	Shielding*	Excitation Levels	Responses	Maximum Observed Current Induced
Fargo, North Dakota	10 dB	140 kV/m	Upsets No Damage	2 A
Shiner, Texas	10 dB	50 kV/m	Upsets Some Damage**	N/A
Vega, Texas	40-50 dB	50 kV/m	Minor Upsets No Damage	N/A
New Hope, Ohio	10 dB	50 kV/m	Upsets No Damage	N/A

EXHIBIT 5-26. Simulated HEMP Tests Of Microwave Relay Facilities.

6.0 SWITCHING SYSTEMS

6.0 SWITCHING SYSTEMS

Two of the switching systems identified as critical assets in Chapter 3.0 are reviewed in this section: 5ESS and 4ESS switches. This chapter analyzes the expected EMP response of both of these switches. In this analysis the following EMP issues and associated practices are discussed:

- EMP shielding effectiveness of building construction and expected field levels
- EMP-induced surges on power lines and communication cables and the effect of these surges on interface equipment to the switch
- EMP penetrations through ground systems.

The next section describes the central office, with emphasis on the EMP stress levels for these switching systems. The remaining sections describe in detail the effects of EMP on each switching system.

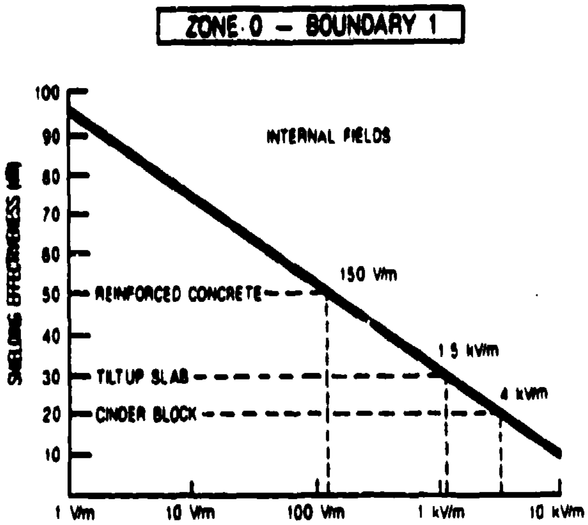
6.1 CENTRAL OFFICE STRESS LEVELS

Assessment of the survivability of switching equipment requires the determination of the stresses due to the diffusion field (zone 1) and the conducted stresses on external penetrators (cables, water pipes, antennas, towers, etc.). The sum of all of these stresses is used as the composite stress for a worst-case assessment.

6.1.1 Field Levels

Since the advent of the electronic switch, plant designers have recognized the need to provide a quiet electromagnetic environment for the switch and associated equipment. In an urban environment, this is typically provided by the use of electromagnetic shielding and filters on power lines to reduce the electromagnetic interference from radio frequency (RF) sources. Switching sites located away from metropolitan area, however, may be in quiet electromagnetic environments, and require little shielding. Most central offices in the PSN are of this latter type, although there is a trend toward increasing levels of RF interference in both urban and rural areas. AT&T standards and practices indicate that these buildings are normally constructed in one of three ways (as discussed in Sections 4.3, 4.4.3): (1) reinforced concrete, (2) pre-formed concrete, and (3) cinder block with brick veneer facing.

The high-altitude EMP threat presents a peak electromagnetic field of about 50 kV/m. Given this external field, Exhibit 6-1 presents the field environment inside zone 1 as a result of shielding provided by the three types of construction. For example, a reinforced concrete building could reduce the fields in zone 1 to about 150 V/m.



NOMOGRAM FOR INTERNAL ELECTRIC FIELD ENVIRONMENTS (ZONE 1)

$$S.E. = 20 \text{ Log} \left(\frac{E_{ext}}{E_{int}} \right)$$

ASSUMED 50 kV/m EMP ENVIRONMENT

EXHIBIT 6-1. Building Shielding Effectiveness.

At some central offices, additional shielding is required because of EMI considerations. This added shielding may be provided by internal shields in the form of conductive screens inside the plant walls, screen rooms for equipment, or shielded cabinets for sensitive electronics. These shielding practices are not a standard procedure, but are usually incorporated into building design and modification as options, depending on site location and circumstances. For example, if a switching system is to be located near an airport with radar and air traffic control equipment that radiates high electric fields, equipment may be placed inside a screen room to protect it from this interference.

Internal shielding can be very effective in reducing diffused field EMP. Some estimates of the shielding effectiveness of internal shielding are (Ref. 14):

- Screen room (60 dB)
- Wire screens (20 dB)
- Inadvertant shielding (possibly 6 to 10 dB).

Inadvertant shielding arises from the standard practice of placing switches near the building center where other metallic equipment such as cable trays, water pipes, and heat ducts may shield the switch. Another form of inadvertant shielding is due to the frames, cabinets, and equipment racks of the switch. Testing of a 1ESS at the Apache Junction Autovon Station (Ref. 26) with a parallel plate illuminator showed that 6 ns rise time fields of 35 kV/m were attenuated 15 to 20 dB with rise times slowed to greater than 80 ns. The resultant effect is similar to that of a lossy low-pass filter. Various polarizations were also injected into the switch area and indicated negligible variation in the responses. In addition, fields shielded by building construction are randomly polarized.

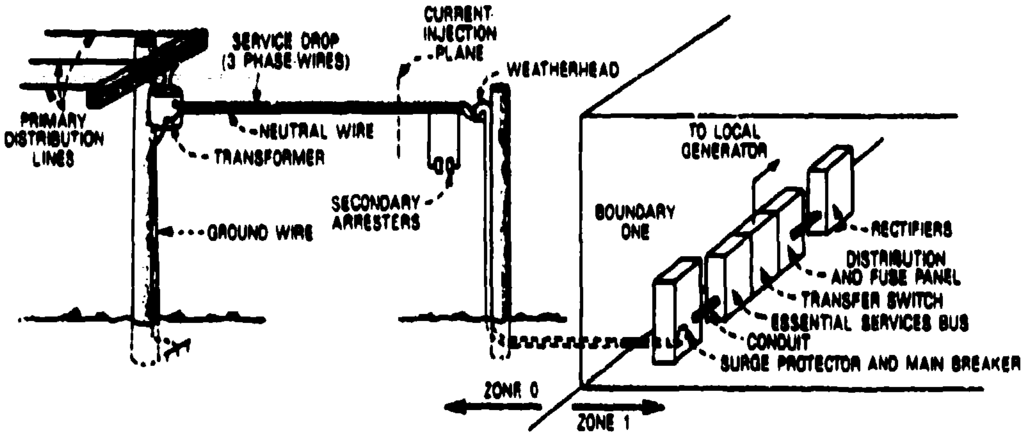
Tests at Apache Junction and Fargo microwave stations measured the building transfer functions (shielding effectiveness), where Apache Junction had a 2 psi overpressure construction and Fargo had a 0.5 psi overpressure construction (see Section 4.4.3). Since shielding effectiveness is a function of frequency, the measurements were made over a wide range of frequencies (100 kHz to 70 MHz). The minimum shielding observed at each site was 25 dB and 10 dB respectively for electric fields, and 15 dB and 0 dB for magnetic fields. These observations support the correlation of building construction and shielding effectiveness (Section 4.4.3) in the EMP frequency range.

The net shielding of the facility is also influenced by apertures, which include windows, doors, wall seams and joints, air conditioning ducts, and other openings in walls, floors, and ceilings. Apertures allow additional penetration of electromagnetic fields (see Section 4.4.3). The size of apertures and their proximity to critical electronics are usually reduced to minimize electromagnetic interferences. Apertures do not significantly affect the shielding of switching facilities. Measurements of shielding effectiveness of typical building constructions include the effects of apertures (Ref. 1), hence the influence of apertures is already incorporated in the present analysis.

6.1.2 Power Line Transients (Zone 1)

The previous sections of this report (Chapter 4) have presented the typical stress values expected on external penetrations and the stress levels brought into the central office from transmission facilities (cables, waveguides). The power lines entering the control office are also significant penetrators. In fact, unshielded aerial power lines may result in 4 kA transients at the power entry to the building (see Section 4.2.1).

Power lines are unique since they are often routed through the building in conduit and are not exposed inside a building. Outside the building, power lines are terminated in a transformer, reducing the voltage to that required by the site. Exhibit 6-2 shows a typical power line termination at a building. Another typical configuration is placement of the line going to the weatherhead pole in an underground conduit.



TYPICAL COMMERCIAL POWER FEED AND DISTRIBUTION BOUNDARY ONE AT THE MAIN BREAKER BOX

EXHIBIT 6-2. Typical Power Line Termination.

Inside the building, the power first passes through the main circuit breaker and then branches to essential and nonessential (i.e., lighting) service buses. From the essential service bus, the power goes to a transfer switch (actuated when power fails), then to a fuse panel and power distribution board (the rectifiers powering the facility are fed directly from this board). These circuits are almost always protected from lightning by the power company serving the physical plant. The power company places lightning arrestors (usually carbon block or gas tube) at the transformer on the load side of the power lines. Also, in virtually all physical plants, the telephone company places its own (secondary) lightning arrestors in the form of carbon block or gas discharge tubes at the weatherhead or at the main breaker when no weatherhead is used.

The coupling through the transformer does not take place by normal transformer action. Common mode currents couple through the capacitance between the transformer windings and through the inductance of the bushings and the leads (Ref. 29). Since this coupling effect is not well understood, no reduction in current on the power line is assumed when passing through the transformer.

Lightning arrestors may also affect the incoming surge, though insufficient data are available about their effectiveness in limiting the fast-rising EMP transients. This is especially true for carbon blocks where the response time for "clamping" may be too slow to be effective. Tests by Bell Labs and the Stanford Research Institute (Refs. 50, 51) on secondary arrestors show reductions in currents of 6 to 15 dB. In view of the uncertainties and limited data, a 6 dB reduction in current is assumed when arrestors are present.

The coupling of the 4 kA signals to equipment at and beyond the rectifiers has been determined through several tests (Refs. 27, 32, and 33). Current injection tests were used to measure the coupling-loss factor to transform exterior currents to interior load currents. (The coupling-loss factor is the ratio of measured peak equipment lead current to peak injected current.) The results of the tests conclude that at the rectifiers, a 4 kA signal is reduced by 40 dB (or 40 A). For nonrectifier leads, the coupling-loss factor is 70 dB (or 1.5 A). Thus, power lines generally contribute little to total induced lead currents (with the exception of rectifier leads) in the buildings tested.

6.1.3 Ground System Transients

The central office ground is a common point to which all ground connections are made to avoid potential differences. The central office ground is typically obtained by connection to the metallic water system. Driven ground rods may be used in addition to, or in lieu of, the water pipe. Inside the central office, low resistance connections to the central office ground are provided throughout the building. The low resistance connections are attained through the use of large diameter cables, copper or aluminum bars, structural steel, etc. All groundable metallic penetrators entering the central office are required to be well bonded to the central office ground. All equipment racks and other metallic surfaces are bonded to the central office ground. Emphasis is placed on maintaining potential equalization between equipment ground, power ground, cable shields, protection ground, and the central office ground.

All ESS equipment is to be bonded to the central office ground using a single point ground; all equipment grounds for the switch are electrically isolated from all other grounds except through a single point. Because EMP transients will cause large potential differences between points in the grounding system due to its self-inductance, large potentials may exist between pieces of equipment that are grounded to different points in the grounding system. Single-point grounding ensures that all of the equipment in the switch is referencing the same ground potential, regardless of the potential between that point and remote earth.

The amplitude of current transients in the ground system are difficult to predict. The currents on all well-bonded penetrators (e.g., waveguides, well-bonded cable sheaths, water pipes, etc.) are all injected into the ground system. Portions of the currents on singly-bonded penetrations also contribute to ground system transients. The transients on power lines and all of the currents diverted through surge protection devices are placed on the ground system. The combination of all of these currents (possibly 100 kA or greater) may cause large potential differences to exist between subsystems unless good bonding and grounding practices are used.

6.1.4 Equipment Lead Transients

EMP-induced transients on the signal leads to switching system equipment include components arising from two sources: conducted transients on conductors external to the central office (zone 0); and coupling to long conductors inside the central office (zone 1). This section summarizes the procedure for estimating the transients on switching system leads based on these two effects.

External conductors (both signal lines and power lines) are attached to various pieces of interface equipment before entering the switching equipment. The interface equipment includes modulators/-demodulators, multiplexers/demultiplexers, equalizers, office repeaters, lightning protection devices, and other terminations. The interface equipment attenuates the transient on the line, providing some amount of protection for the switching equipment. However, the attenuation is extremely difficult to predict without detailed knowledge of the circuit design of the interface equipment, and few test data exist. A worst case attenuation of 0 dB (no attenuation) is assumed unless measured attenuation data exist for a particular piece of equipment. The transient levels on transmission facilities are described in detail in Chapter 5 and are summarized in Exhibit 6-3. These levels are assumed to also exist at switching system input leads that connect to these transmission facilities.

Transmission Facility	Peak Current (App)
T1	15
TD-2	1

EXHIBIT 6-3. Central Office Stress Levels On Transmission Facilities.

As seen in previous sections, coupling to conductors within the central office has two sources: the EMP fields within the building (direct illumination); and coupling due to the currents induced on external conductors tht are brought into the building (penetrations). Diffused EMP field coupling to wires within the central office is covered in detail in Section 4.3 A summary of the results is presented in Exhibit 6-4.

			Peak-to-Peak Current (A)	
	f_0(MHz)	$t_{1/e}$(s)	Concrete Block	Poured in Place
Average	7.2	4.6	10.0	0.3
Median	6.3	4.3	6.0	0.3
Range	1-16	1-8	3-20	0.2-5.0

EXHIBIT 6-4. Induced Current Waveforms From Direct Illumination

Coupling from penetrations depends on penetrator transients, routing of the penetrations within the building, routing of the equipment lead of interest, and bonding of conductors. However, the currents induced on the equipment leads as a result of the penetrators may be estimated based on existing data bases of EMP test results (Refs. 11, 12, and 13).

The estimation of currents on equipment leads is a two-step process. The first step is the estimation of the current induced on the penetrator. Induced currents on typical penetrators for a central office are described in detail in Chapter 4. Measured coupling-loss factors from EMP testing are used to calculate the induced current on equipment lead as a result of the current on the penetrators. The coupling-loss factor is defined by $\alpha = 20 \log (Ip/Ie)$, where α is the coupling-loss factor, Ip is the peak-to-peak amplitude of the current on the penetrator, and Ie is the peak-to-peak amplitude of the current on the equipment lead.

Measured coupling-loss factors are greatly affected by bonding to the central office ground system and proximity of equipment leads to the penetrators. Penetrators that are well bonded to the building ground, including waveguides, coaxial cable sheaths, some aerial cable sheaths, water pipes, and sewer pipes, exhibit relatively large coupling-loss factors; unbonded or singly-bonded penetrators exhibit relatively small coupling-loss factors. An example of a singly-bonded penetrator is an unshielded telephone line with a surge arrestor for lightning protection. Unbonded penetrators include unbonded twisted pair cables and commercial radio antennas.

For simplification of the estimation procedure, the proximity of equipment leads and penetrators is separated into two cases: near zone and far zone. The equipment leads are considered to be in the near zone if the switching equipment is within 3 m of the penetrator. If there are more than 3 m of separation, it is considered to be in the far zone.

The peak-to-peak amplitudes of penetrator currents and the measured coupling-loss factors for equipment leads are summarized in Exhibit 6-5. The coupling-loss factor for power lines to all equipment other than switching system equipment leads is 70 dB. The coupling-loss factor between equipment leads for all well-bonded penetrators is 45 dB for the near zone, and 65 dB for the far zone. The coupling-loss factor between equipment leads and singly bonded penetrators is 36 dB for the near zone and 65 dB for the far zone. The coupling-loss factor between equipment leads and unbonded penetrators is 30 dB in the near zone and 65 dB in the far zone.

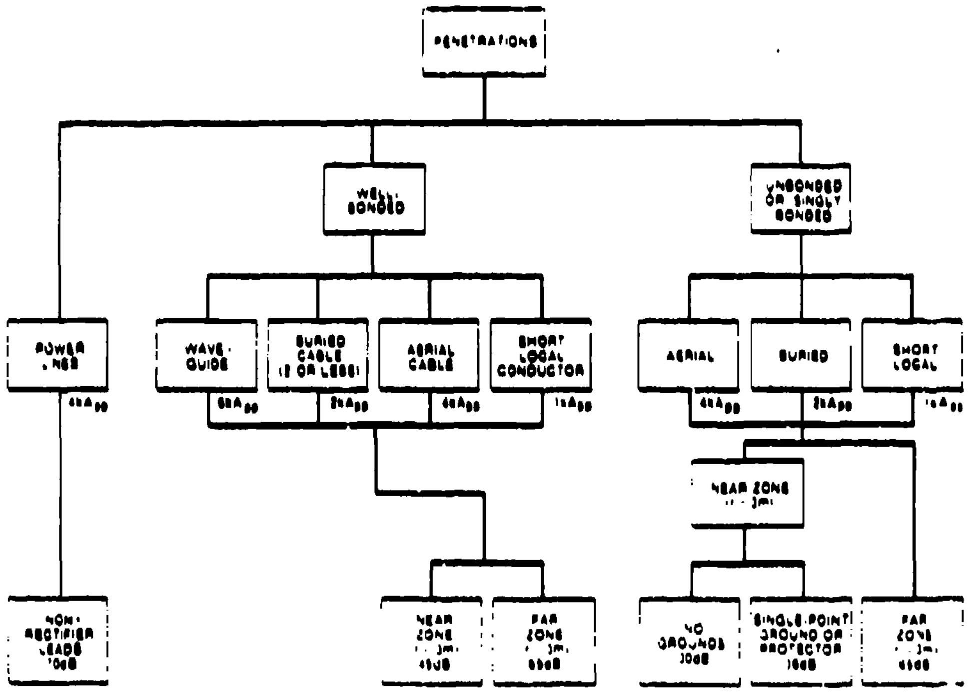


EXHIBIT 6-5. Summary of Penetrator Currents and Coupling-Loss Factors.

The estimated peak-to-peak amplitude of the transient current on the switching system equipment leads is the sum of all of the contributing effects described above. For example, consider a switching system located in a concrete block central office. If the lead of interest is connected to T1 carrier, the direct contribution from the external cable is 15 A (from Exhibit 6-3). The current from direct illumination is 20 A (from Exhibit 6-4). If the system is in the near zone of the well bonded T1 carrier, the current contribution from the sheath current of the T1 is 22 A (from Exhibit 6-5, 4 kA decreased by 45 dB). The contribution from a waveguide (far zone) is 3 A (from Exhibit 6-5), 6 kA decreased by 65 dB). The current from the power lines is 1 A (from Exhibit 6-5), 4 kA decreased by 70 dB). Finally, the current induced by the water line that enters the building (far zone) is 0.6 A (from Exhibit 6-5), 1 kA decreased by 65 dB). The estimated total transient on the signal leads is the sum of each of these components, or 62 A, peak-to-peak.

6.2 5ESS SWITCHING SYSTEM*

The 5ESS switch is a time-division, digital switching system, consisting of a complex combination of hardware and software. There are three major hardware components of a 5ESS switch: the Administrative Module (AM), the Communications Module (CM), and the Switching Module (SM). A block diagram of a 5ESS switch is shown in Exhibit 6-6; the exact configuration is customized to meet the requirements of each particular office.

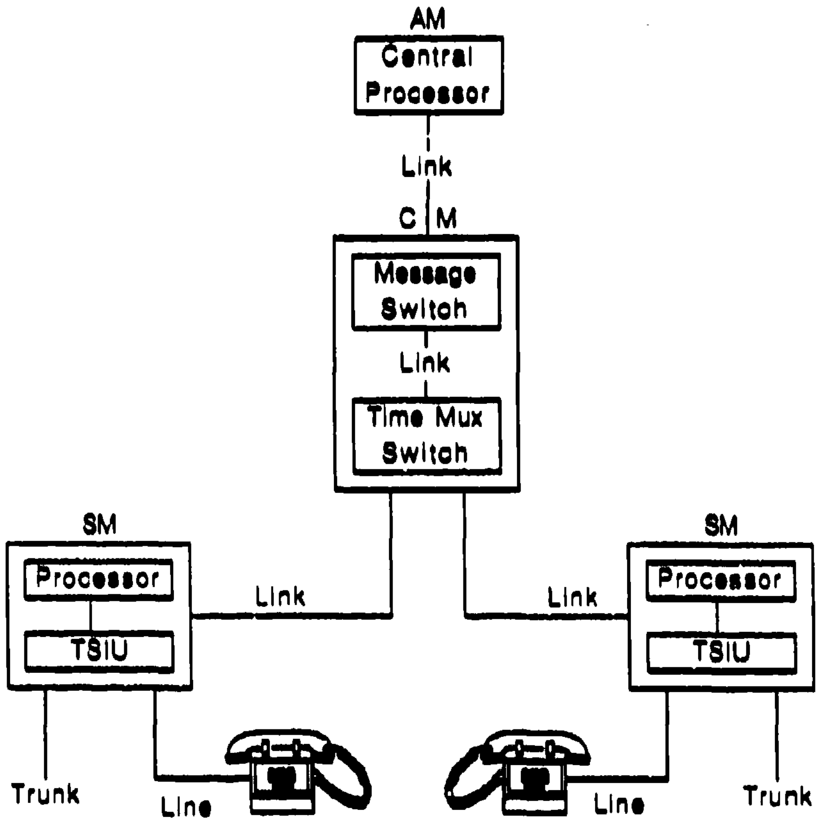


EXHIBIT 6-6. Functional Diagram Of The 5ESS Switching System.

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* Significant portions of this section are drawn from NCS TIB 86-3 entitled "Nuclear Weapons Effects Studies for the 5ESS™ Switch," which summarizes work performed by AT&T for the NCS under Contract Number DCA100-85-C-0094.

At the heart of the AM is the central processor, an AT&T 3B20D fully-duplexed computer. It handles allocation of resources, overall maintenance, and interface with operation support systems. The two major components in the CM are the Message Switch (MSG) and the Time Multiplexed Switch (TMS). The MSG directs the routing of control, maintenance, and administrative messages between the AM and the SMs. The TMS performs time-multiplexed, space-division switching of digitized voice signals, internal system messages, and synchronization pulses.

The SMs are microprocessor-based units that provide the majority of normal call-processing functions. They serve as the terminations of all transmission facilities entering the switch, including both lines and trunks. Such terminations include all required equalization, amplification, and digital-to-analog and analog-to-digital conversions. Each SM also contains its own time slot interchange unit (TSIU) that performs time division switching for all connections required between two channels within the module. Connections involving two SMs uses the TSIUs of both of the SMs and the TMS to form a time-space-time network.

The 5ESS system supports the use of remote switching modules (RSMs) similar in design to 5ESS interface modules. The main difference is that RSMs may be located up to 100 miles from the main (host) 5ESS system, usually connected by T1 lines. The RSM terminates up to 4,000 customer lines and performs all switching functions between lines that are terminated by the same module. All other connections are passed through the TMS of the host system.

Stored programs run by the distributed microprocessors in the AM, CM, an SMs control the 5ESS switch. The distributed memories in a switch store both office-specific data and program software ("generics") which is common to a whole class of switch. 5ESS switch software controls the operating system, call processing, and system administration and maintenance.

Fiber optic cables are used for all communication between the control processor, the MSG, the TMS, and all of the SMs within the central processor. The format of the lines is a serial PCM digital signal transmitted at 32.768 Mbits/s. This format contains 256 time slots per optical fiber. Because fiber optic cables do not directly couple to electric fields, the signals internal to the switch itself are relatively isolated from EMP interference.

6.2.1 System Response to Direct Illumination

The 5ESS switch does not require any special electromagnetic shielding techniques in the central office; therefore, the incident electric field is as described in Section 6.1.1. The EMP field tests of the 5ESS switch were conducted at the Air Force Weapons Lab (AFWL) test facility in Albuquerque, New Mexico. The model office was tested under two EMP simulators. At the first facility, known as the ALECS facility, the equipment was exposed to planar, vertically-polarized fields of between 5 kV/m and 80 kV/m. At the second facility, known as the Horizontally Polarized Dipole (HPD), the switch was exposed to spherical, horizontally-polarized fields of 35 kV/m. The fields produced by

ALECS exceeded the 15 kV/m vertically-polarized component of the threat specified for this assessment. The fields produced at the HPD did not meet the 50 kV/m horizontally-polarized component of the threat waveform, although the 35 kV/m field exceeded the field expected inside many buildings. A 50 kV/m pulse incident on a building offering only 3 dB of shielding would result in a 35 kV/m pulse inside the building itself. The results of the HPD tests were consistent with the results of the ALECS tests, verifying that the results for the vertically-polarized ALECS fields held for horizontal polarizations as well.

At all levels of testing, some form of system upset occurred. The faults and upsets that occurred are separated into three categories: "hardware failures," which resulted in physical damage requiring replacement of hardware; "manually recoverable hardware upsets," which required human intervention to restore switch functionality; and "recoverable logic upsets," which resulted in temporary switch disruption, with the switch returning itself to full operation without human intervention. The main focus of this test was to determine whether exposure to simulated EMP would result in a loss of service; temporary, automatically recoverable upsets (requiring no human intervention) were of lesser concern.

6.2.1.1 Hardware Failures

The 48 V power system for the 5ESS system (shown in Exhibit 6-7) is consistent with the discussion of power systems in Section 6.1.3. The commercial AC power is rectified by three 200 A Lineage 2000 rectifiers (model J87439A) arranged in parallel with the 48 V battery set and a battery plant controller. Whenever a loss of AC power occurs, the controller transfers the electrical load from the rectifiers to the battery set. Each rectifier alone was capable of fully powering the switch, although the three rectifiers were generally placed on-line together to share the load, providing the system with a redundant power-supply capability.

Several pulses above 50 kV/m caused the failure of several power diodes in the rectifiers, leaving the affected rectifier(s) inoperative. One test pulse caused the AC circuit-breakers of all three rectifiers to trip, resulting in a switch to battery power. Every DC-to-DC power converter in the 5ESS switch also shut down, causing the operation of the entire switch to stop. The diode failure was probably in response to voltage transients which exceeded the 200 V peak reverse voltage (PRV) rating of the diodes. Diodes rated at 800 V PRV were installed, and the modified rectifiers were exposed to pulses at ALECS up to 80 kV/m vertical without a single diode failure or power shutdown, although they were never exposed to the horizontally-polarized fields of the HPD. The massive power-down shows that the unmodified rectifiers can not be considered survivable to the effects of EMP. Even a switch to battery power is unacceptable, because the batteries will only provide power for a limited amount of time. If the failed rectifiers are not repaired before battery power is lost, operation of the entire 5ESS switch will cease.

AT&T plans to use the 800 V PRV diodes in all Lineage 2000 rectifiers produced as of September, 1986. The modified model J87439A

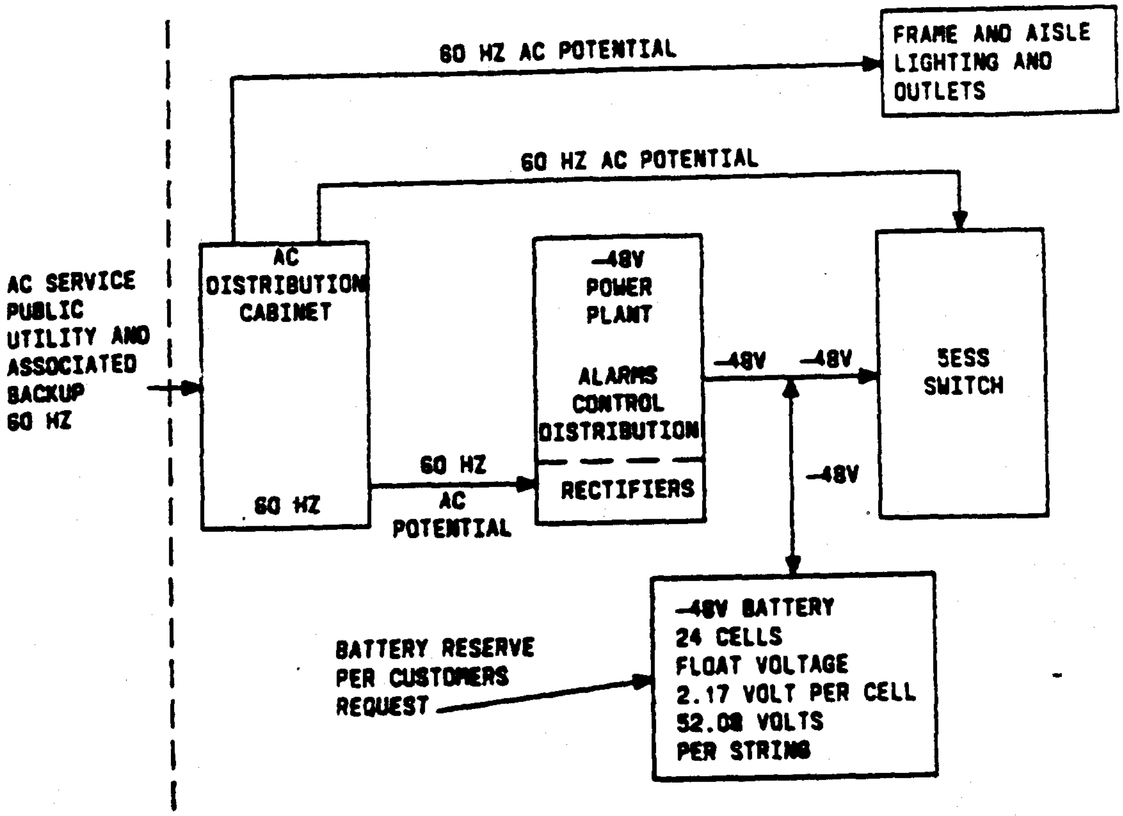


EXHIBIT 6-7. Power System Of The 5ESS Switching System.

rectifiers survived the effects of the vertically-polarized fields of ALECS, but because they were never subjected to the horizontally-polarized fields of the HPD, their survivability to EMP is undetermined. Model J87439A rectifiers are currently being replaced with a new model. Other models rated at 100 A and 400 A will soon be introduced, as will a line of lower-capacity rectifiers. Because these new rectifiers vary considerably in design from the model used in this test, further testing is needed to assess their vulnerability to EMP.

Induced transients also caused damage to battery plant controller (Microprocessor and Conventional Controller Systems) components and shutdown of a single rectifier. The occurrence of the particular problems were highly variable, although it was suspected that the shutdowns were caused by a rectifier problem. No solution was suggested for these problems, so it is likely that they will occur again during exposure to actual EMP. While these problems did not cause the switch to stop operating or to lose its call processing capability, further testing is needed to determine their cause and to verify that the battery plant controller is survivable to EMP.

The Master Control Center (MCC) terminal or printer communicates with the 5ESS switch AM through an RS-232C copper-braid shielded cable. Current injection testing of the TTY interface showed that transients as small as 175 V and 4 A were sufficient to damage the RS-232C receive circuit. Therefore during testing, the cables were replaced with RS-232C optical fiber links, which do not conduct large transients. On the final day of testing, the optical fiber links were replaced with the shielded cables, and permanent hardware failure occurred after just three pulses, verifying the predicted vulnerability. The susceptibility of the MCC and MTTYC interface to EMP-induced damage when using hard-wire cable connections makes it essential to provide protection if equipment is to survive. While optical links and modems are available as a well-tested option, they are not normally used in most 5ESS switches because they are more expensive than conventional copper-braid shielded cable.

6.2.1.2 Manually Recoverable Hardware Upsets

Unless an EMP-hardened link connects the switch to a central office, certain types of faults will require manual intervention to restore full service. This is a very serious problem, because switches in remote or isolated locations may not manually be returned to service for many days .

Pulses as low as 5 kV/m vertical caused several units within the AM to hang-up due to logic upsets within the Power Control and Display Circuits. The problem was solved by reducing the value of a pullup resistor. Slightly higher field levels caused power converter and interface circuits in the switching module to deactivate. The power converter problem was solved by replacing power control circuitry with a newer, less noise-sensitive version. The interface circuit problem was solved by placing a single filter capacitor across a latch input. A similar correction prevented shutdown of the power supplies to the AM moving head disks (MHDs). Additional testing at fields as high as 80 kV/m vertical and 35 kV/m horizontal verified that all the modifications successfully eliminated the faults (only one upset was observed during the 2550 tests of the modified circuitry). AT&T has adopted these circuit modifications for use in production models of the 5ESS switch; the modifications appear to solve the sensitivity problems, but assuring survivability of a particular system requires ensuring that these circuit modifications are used in that system.

6.2.1.3 Recoverable Logic Upsets

The operation of many different electronic circuits in the AM, CM, and SM was disrupted by exposure to fields of all levels, causing stable calls to be dropped and the call processing capability of the switch to be reduced temporarily. The mean fraction of stable calls dropped after a single exposure (as shown in Exhibit 6-8) is between 16% and 46%. The vertical bars represent a one-standard deviation variation in the fraction of stable calls dropped. Following several repeated exposures, a mean fraction of 93% ± 8% of the stable calls were dropped, while at field levels over 45 kV/m, virtually no calls could be completed for several minutes.

Immediately following exposure to simulated EMP fields, the switch began automatic fault recovery to isolate the fault and to restore the call processing ability of the switch. As shown in Exhibit 6-8, the efficiency of the switch in completing calls gradually increased as the time from exposure increased, but the switch never achieved full recovery, with the efficiency lowest following repeated exposures. With the efficiency less than 100%, service was not restored to some loops or trunks, and the likelihood of call blocking occurring increased.

With assistance from an operator at the MCC, the call completion efficiency reached greater than 99% after about 30 minutes, provided an optical link connected the MCC and 5ESS switch. It must be stressed that because many central offices with 5ESS switches are not staffed, prompt restoration of service could not be guaranteed unless remote switching control centers (SCCs), with survivable links to the CO, exist.

6.3 4ESS SWITCHING SYSTEM

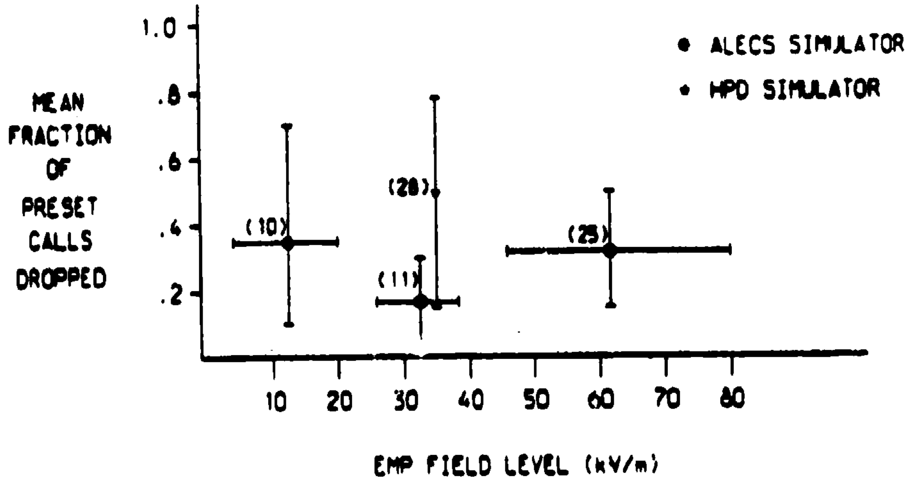
The 4ESS is a time-division, digital switching system designed for use in toll applications. Similar to the 5ESS, the switching network of the 4ESS switch is comprised of Time Slot Interchange (TSI) and Time Multiplexed Switch (TMS) frames interconnected to form a time-space-time network. The 4ESS is of fundamental importance in the PSN because of its prevalence and its significance in the hierarchical switching structure.

The 4ESS switch (see Exhibit 6-9) contains several frames that terminate trunks and convert signals to suitable format for input to the TSI. The Digital Interface Frame (DIF) terminates up to 160 DS-1 format signals and multiplexes them onto 32 lines. DS-1 format signals include T1 carrier and the output of other frames used for trunk terminations. In contrast to the electromechanical switches, the 4ESS system is designed to use the digital carrier signals directly, without conversion to analog signals.

The LT-1 connector terminates two 12-channel analog group signals and transmultiplexes them onto one 24-channel DS-1 signal. This connector is used to terminate analog carrier systems in the 60 to 108 kHz frequency band. The output of the LT-1 connector is suitable for connection to the DIF.

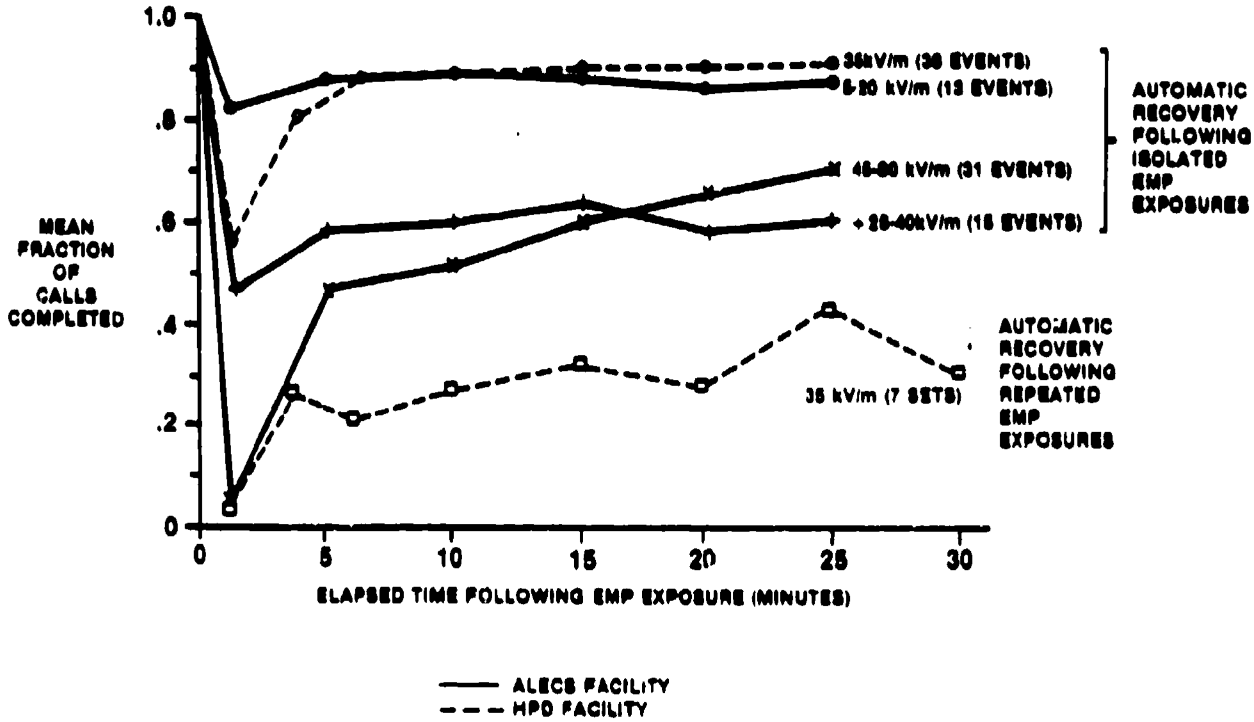
Metallic trunks, international format analog carrier trunks, and other miscellaneous voice frequency circuits are terminated in a D4 channel bank. A D4 channel bank terminates the lines, performs analog to digital conversion, and multiplexes the digital signals onto a DS-1 format line, which is connected directly to the DIF.

The entire 4ESS system is controlled by the 1A processor. The processor monitors and controls the operation of all of the other subsystems, establishes and maintains trunk interconnections, and performs self-checking to locate faulty circuits. As a stored program control system, the 4ESS system maintains all of the instruction for the processor in semipermanent memory to maximize flexibility and to facilitate rapid implementation of new instruction sets.



The horizontal bars span the field levels that apply to the given data point; ( ) = number of events.

(a) Mean Fraction of Preset Calls Dropped Due to Induced Transients



(b) Automatic Recovery of Call Processing Following Simulator Exposure

EXHIBIT 6-8 Transient-Induced Effects on Telecommunications Network.

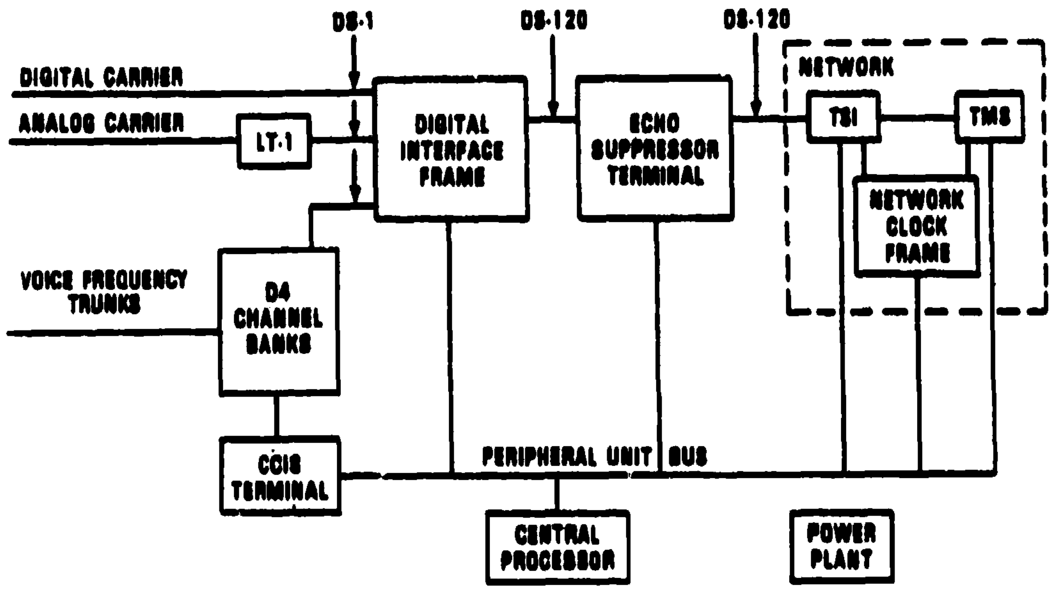


EXHIBIT 6-9. Functional Diagram Of The 4ESS Switching System.

All of the frames communicate with the processor via the peripheral unit bus (PUB). The processor uses the PUB to send commands to the other subsystems, to receive responses from them, and to collect maintenance information. The DIF and D4 channel bank both use the PUB to transmit signaling information that is extracted from the trunk lines.

6.3.1 System Response To Direct Illumination

The 4ESS system does not require any special electromagnetic shielding techniques in the central office; therefore, the incident electric field is as described in Section 6.1.1. The 4ESS switch is designed to the requirements of the Local Switching System General Requirements (LSSGR) (Ref. 61) to operate without degradation while subjected to an electric field with a peak amplitude of 10 V/m for any frequency between 10 kHz and 1 GHz. This electric field specification is consistent with the Bell System Practice (BSP) dealing with the radio frequency interference of switching systems (Ref. 14). This electric field specification is the guaranteed minimum operational upset threshold; for this assessment, the damage threshold is of interest. As stated previously in this report, a margin of 30 dB to 40 dB can be expected between the upset threshold specification and the damage threshold. Therefore, the damage threshold of the 4ESS can be estimated to be at least 300 V/m.

The 4ESS system has not been subjected to EMP testing to determine actual susceptibility to electric fields. The equipment is contained in open equipment racks, which offer minimal electromagnetic shielding for the equipment. Several internal conductors may be long enough to couple sufficient energy to cause equipment damage. The signal lines between the DIF and the TSI, and those between the TSI and the TMS are coaxial cables; the shielding of these lines should prevent appreciable transients from being induced on the center conductor and causing damage. The PUB consists of unshielded twisted pair cables that must connect to each frame within the switch, possibly reaching a length in excess of 100 m. The PUB is never in the near field of any of the penetrators described in Section 6.1.4; however, the current due to the diffused electric field may be as high as 20 A, peak-to-peak. The PUB is connected to line driver/receiver circuit pacs, which are designed to withstand transient overvoltages associated with transmission lines. However, detailed analysis and/or testing is required to accurately assess the survivability of a 4ESS system subjected to EMP fields.

6.3.2 System Response To Power Lead Transients

Power for the 4ESS subsystems is passed through the AC distribution equipment, transfer switch, and rectifier described in Section 6.1.2; the output of the rectifier charges a 140-V battery plant that supplies power to the 4ESS system. The output of the battery plant is connected to bulk dc-to-dc converters in the switch. The 24- or 48-V output of these converters is distributed to in-frame dc-to-dc converters located in each rack of 4ESS equipment. The output voltage of the in-frame converters ranges from -28 to +28 V, depending on the requirements of the equipment in the racks.

As described in 6.1.2, little of the 1 kA transient on commercial power lines is expected to pass through the rectifier to the battery plant. Any transient passing through the battery plant is then attenuated by the large capacitances of the two dc-to-dc converters before entering any circuit pacs in the equipment. For these reasons, transients on the power leads of the 4ESS system are not likely to be large enough to cause permanent damage; however, EMP testing of the power system is required to verify this conclusion.

6.3.3 System Response To Signal Lead Transients

Estimation of the signal lead transients for switching systems is discussed in Section 6.1.4. The 4ESS system is typically placed in the center of the central office; as far away from any penetrators as practical. Therefore, the equipment attached to signal leads is assumed to be in the far zone from all penetrators. Although the actual estimation depends on which penetrators are present in the central office, reasonable estimates of the transients on signal lines are 40 A for concrete block construction and 25 A for reinforced concrete construction.

The vulnerability of the D4 channel bank is addressed in Section 5.1.4. Based on field testing, both the digital inputs (receive units) and the voice frequency inputs were found to be vulnerable to damage as a result of EMP transients. The DIF is similar in technology, function, and application to the D4, and may be presumed similar in survivability. The LT-1 connector inputs are sufficiently different from any D4 inputs that no conclusions can be drawn about their survivability. Detailed analysis and EMP testing are required to conclusively assess the survivability of these interfaces for the 4ESS switch.

6.3.4 System Response To Ground System Transients

Transients in the central office ground system are described in Section 6.1.3. As with the 5ESS system, the 4ESS switch utilizes a single point ground, which provides isolation from transients in the ground system. Large current transients in the ground system may cause differences in potential between the ground connection of the switch and that of the peripheral equipment. Such potentials may cause large potential differences between the leads on the peripheral equipment and those on the switch; the resultant current may damage the equipment attached to the leads. Much of the equipment required to convert signals to the internal format of the 4ESS switch is included in the switching system itself; this equipment shares the single point ground with the rest of the system. As more peripheral equipment is included within the switch itself, the single point ground system is increasingly effective at mitigating the effects of transients in the ground system.

6.4 SUMMARY

With the hardware modifications discussed in Section 6.2 in place, the 5ESS switch and associated power system suffered no permanent hardware damage. The switch remained operational following exposure to threat-level fields, but a significant fraction of calls were dropped and call processing capability was reduced. Automatic recovery slowly restored call processing efficiency but never to 100%.

5ESS power systems produced before September, 1986, were shown to be susceptible to induced transients. Modified power system rectifiers were shown able to survive threat-level vertically-polarized fields, but because they were never subjected to threat-level horizontally-polarized fields, their survivability remains undetermined. Power is supplied by batteries as a result of a complete shutdown of the rectifiers, but this is only a temporary solution to the problem; once battery power is lost, the 5ESS is rendered completely inoperative.

For upsets not caused by hardware failures, the switch can be restored to full operation by an operator at the MCC, provided the switching office is staffed, or by an operator at the SCC, provided the SCC and its link to the CO are survivable. It must be emphasized, though, that many COs are not staffed, and projections call for even less staffing in the future. The links between remote SCCs and COs have not been shown to be generally survivable, and there are no plans to either retrofit existing links with survivable ones or install survivable links in new systems. Because it is quite likely that the CO is not staffed and the remote SCC links are not survivable, realistic expectations dictate that the 5ESS switch is not survivable to EMP exposure.

Available data are insufficient to determine the efects of EMP on the 4ESS switching system. Conclusions about the survivability of the 5ESS switching system cannot be directly applied to the 4ESS system, because their technologies are fundamentally different. Because no EMP test data exist for the 4ESS system, conclusions about the survivability of 4ESS switching system must be based on implications of related EM test data and the use of elecromagnetic protection practices. However, available data are sufficient to make observations concerning potential strengths and weaknesses of the systems.

The survivability of the 4ESS switching system against EMP fields is greatly affected by the use of open equipment racks and the use of long, unshielded wires for the PUB. The use of extensive filtering in the power distribution system and the use of a single point ground system should provide significant protection for the 4ESS equipment. The D4 was shown to be vulnerable to typical EMP conducted transients; in the absence of test data the DIF must be presumed similar in vulnerability to the D4.

The observations presented here are only indications of potential strengths and weaknesses of the 4ESS system in a EMP environment. Conclusions about its response to EMP require more detailed analysis and the results of EMP simulation testing of typical configurations of this system.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.0 CONCLUSIONS AND RECOMMENDATIONS

Section 7.1 summarizes conclusions drawn in other chapters about the performance of the assessed systems after exposure to HEMP fields; Section 7.2 makes recommendations concerning future activities for the NCS EMP Mitigation Program.

7.1 CONCLUSIONS

Conclusions concerning the effects of EMP on selected network elements are as follows:

- The T1 carrier system is vulnerable to the effects of HEMP. T1 system elements have been exposed to simulated HEMP fields; the results were then analytically extrapolated to full threat values. Lightning protected repeaters were not damaged; however, D4 channel banks suffered service-affecting damage during both direct illumination and current-injection testing that simulated the expected central office environment.

- The FT3C multi-mode system is vulnerable to the effects of HEMP. Threat-level fields and injected currents did not produce any signal disruptions or service-affecting hardware damage during testing of the optical cable and splice case; both elements appear to be survivable to the effects of HEMP. Available test data on the survivability of CO and LRS equipment are inconclusive, since threat-level currents were not injected into all subsystems. Unmodified power converters were shown to be vulnerable to threat-level transients. Power converters incorporating several hardware modifications proved robust, although the test configurations using modified power converters were not typical of most LRSs and COs. The modified power converters, therefore, can not be considered survivable to EMP based on available test data. Because both line repeater station (LRS) and central office (CO) equipment rely upon the power converters to power them, the entire FT3C system must be considered vulnerable.

- The L4 and L5 systems are robust to HEMP effects. These systems are designed for survival in a nuclear environment; all cable is buried and repeaters are well bonded and well grounded. Detailed computer analyses and HEMP simulation tests indicate that some temporary system outages will occur, but that no equipment will be damaged as a result of HEMP.

- The TD-2 microwave radio system is survivable to HEMP effects. Threat level, free-field HEMP simulation testing has produced upsets such as the activation of protection switching and frequency shifting, but has produced no failures. Low-level current-injection tests caused no failures. High-level testing has not been done but comparison of predicted HEMP-induced currents to expected lightning-induced transients on microwave towers indicates that TD-2 systems are also survivable against conducted transients.

- The 5ESS switching system is vulnerable to the effects of HEMP. Several service-affecting hardware failures occured under exposure to threat-level fields. With several hardware modifications in place, the hardened 5ESS switch suffered no permanent hardware damage, although a significant number of calls were dropped and call processing capability was reduced. Manual recovery was required to restore call processing efficiency to greater than 99%; however, most central offices housing 5ESS switches are not staffed and the survivability of remote links has not been demonstrated. To ensure the survivability of a particular 5ESS system requires verification that the identified hardware modifications have been installed and verification that either the site will be staffed or that a survivable remote link has been established.

- Existing test data on the 4ESS switching system are insufficient to assess its vulnerability to HEMP. No tests or theoretical analysis of the HEMP response of the 4ESS system exist; the results of the 5ESS system assessment cannot be applied to the 4ESS system. In the absence of test data, no definite conclusions can be drawn.

7.2 RECOMMENDATIONS

Recommendations concerning future efforts in this program are as follows:

- The effects of HEMP on the 4ESS switching system should be determined through test and analysis. The configuration assessed should include typical line termination equipment, including Digital Interface Frames (DIFs), LT-1 connectors, and D4 channel banks. Typical lengths of the Peripheral Unit Bus (PUB) should also be included. The configuration should also include appropriately placed lightning protection devices.

- The results of the current study to determine the sensitivity of the network-level HEMP-effects model should be used to identify and prioritize critical telecommunications assets. The NCS has developed a model to predict the effects of HEMP-induced equipment failures on telecommunications networks. Current efforts include a study to determine the sensitivity of predicted network performance to input data. The telecommunications equipment critical to the NSEP capabilities of the NCS should be identified and prioritized based on the results of the sensitivity study. This prioritization should be used as a basis for allocating resources for future tests and analysis of telecommunications equipment in support of this program.

- Remaining issues concerning 5ESS switching systems should be resolved by testing and analysis. The survivability of remote links to 5ESS sites should be determined. Further testing of existing 5ESS power system rectifiers is needed to verify their survivability. Several new models of rectifiers are planned for use in future 5ESS power systems; these rectifiers must be thoroughly tested before any system in which these are used can be considered survivable to EMP.

- Remaining issues concerning FT3C carrier systems should be resolved by testing and analysis. Threat-level currents should be injected into all CO and LRS equipment subsystems, so that their survivability can be determined. Further testing of EMP-hardened power converters using test configurations typical of most LRSs and COs is needed to verify their survivability to EMP. Single-mode fiber optic systems should be tested to assess their survivability to EMP, and a comparison should be made to the results of the FT3C multi-mode system assessment.

- The HEMP response of TD-3 microwave systems should be evaluated through test and analysis. The TD-2 microwave system is based on vacuum tube technology; the TD-3 system is a solid state replacement for the TD-2 system. Solid state components tend to be less survivable than their vacuum tube equivalents. This evaluation is required to determine if the TD-3 system is as robust as the TD-2 system.

- Remaining issues concerning T1 systems should be resolved by testing and analysis. Not all T1 line repeaters in the PSN are lightning protected. Therefore, T1 repeaters without lightning protection should be tested in typical configurations. In addition, typical splice case configurations need to be tested with current injection on the sheath, as coupling to signal wires from bond straps can be a significant part of the threat to T1 line and office equipment.

- The EMP responses of equipment from different vendors should be analyzed to evaluate methods of relating test results for one system to the survivability of another. Various vendors manufacture similar equipment for the telecommunications industry, e.g., T1 line termination equipment, channel banks, and local, digital switching systems. The ability to relate the survivability of similar pieces of equipment would minimize the amount of testing required to assess the effects of HEMP on telecommunications networks.

The present analysis should be extended to include the new Department of Defense approved HEMP threat (Ref. 2). The analysis should include the early time, mid-time, and late time (MHD EMP) effects. The faster rise time of the new threat can create higher peak level transients on cables and antenna leads. The MHD EMP can create large transients on very long cables. Analysis including these effects may identify additional EMP vulnerabilities in telecommunications assets.

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